DIPLOMARBEIT

Assessment of Grassland Biomass as Second Generation Biofuel Feedstock in Austria

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Contents

Summary

This study examined scenarios for the production of second generation biofuels from biomass of permanent grasslands in Austria. Using a coherent method, this study modelled the input-output balances and output/input ratios of carbon, GHG and energy fluxes during the biofuel life cycles. We used a range of scenarios (27 subsystems) to assess the potential of biofuels, including different grassland management intensities and biofuel conversion technologies for a range of model farms in Austria. We hypothesized that biofuel production from permanent grasslands in Austria would allow to address nature conservation issues (i.e., the conservation of biodiversity and landscape diversity) concurrently with strategies to mitigate greenhouse gas (GHG) emissions from the transport sector and provide a renewable energy supply from domestic sources.

The main results of the study can be summarized as follows:

1. All investigates biofuel life cycles were carbon and GHG positive, i.e. biofuel life cycles were net sources for carbon and GHG, reflecting the wide system boundaries of the study, which accounted for biogenic carbon emissions as well as upstream emissions arising from inputs to the biofuel life cycles. Biomass carbon emissions and net ecosystem exchange of CO_2 were major fluxes exerting a prime control on carbon and GHG balances. Fertilizer-related emissions of N_20 and CO_2 contributed significantly to GHG emissions and were the main differentiating factors for GHG and carbon balances. Fertilizer emissions therefore showed the highest potentials for further GHG reduction in grassland biofuel productions. Methane was taken up by all grasslands, but had little effect on carbon and GHG balances. Overall our work with regard to carbon and GHG emissions demonstrated that the biogenic carbon emissions and N_2O losses were the critical fluxes in the assessments of biofuels. Thus, we conclude that a life cycle assessment of biofuels (a) should be strictly flux-based, (b) should include a change-oriented approach to assess GHG saving potential and (c) should include a quantification of environmental costs of transport services.

2. Net energy ratios (i.e., the ratio of energy output of the produced biofuel to the total energy input for production) for biofuels from Austrian grasslands were rather modest compared to published international reference case studies, reflecting an input intensive grassland management in Austria. In terms of energy yield, the investigated grassland biofuels were comparable to other second generation biofuels from lignocellulosic feedstock.

3. Our study found a trade-off for biofuel production in the optimization of grasslands for carbon sequestration and energy conversion efficiency on one side and effectiveness of GHG mitigation on the other. Low-input grasslands provided the highest GHG savings, while high-

input grassland allowed a biofuel production with the highest energy efficiency, carbon recycling potential and GHG saving per unit of land. However, all investigated biofuel production systems showed net energy gains and lessened GHG emissions of transport services compared to a fossil fuel reference.

4. Biofuel conversion technologies differed in terms of carbon recycling and GHG saving potential as well as for energy conversion efficiency if calculated on a farm level. Combustion of grassland biomass showed the most beneficial energy conversion efficiency and GHG reduction potential, whereas carbon recycling potential was in between the two other conversion processes. Lignocellulosic fermentation, in contrast was found to be the most beneficial for carbon recycling, while GHG reduction potential and energy conversion efficiency were in the lower range of the three processes. Gasification of biomass was the least efficient process modelled for all three indicators.

5. The biofuel production potential for the total grassland area in Austria was also modelled, demonstrating a realistic potential for grassland biofuels to provide a significant part of transport services. We found that a biofuel production from permanent grassland can, especially if grasslands are managed extensively, be a promising strategy to maintain highly diverse permanent grasslands. Additionally, the restoration of reforested, previously abandoned grasslands or of cultivated land, would also lead to augmented soil organic carbon pools and to enhanced biodiversity on a landscape level.

6. In conclusion biofuels from grassland biomass could help to unite goals that were previously thought to be incompatible: GHG mitigation, energy security, rural development and nature conservation.

Kurzfassung

Diese vorliegende Arbeit untersuchte Szenarien für die Produktion von Biokraftstoffen der zweiten Generation aus Biomasse österreichischer Grünländer. Mittels schlüssiger Methodik wurden Input - Output Bilanzen sowie Output zu Input Raten von Kohlenstoff-, Treibhausgas- und Energieflüssen berechnet, die im Lebenszyklus der Biokraftstoffe auftreten. Um das Potential der Biokraftstoffe zu untersuchen, wurden insgesamt 27 Subsysteme verwendet die verschieden intensives Grünlandmanagement, drei Konversionstechnologien und unterschiedliche Modellhöfe beinhalteten. Wir setzten voraus, dass die Produktion von Biokraftstoffen aus Biomasse österreichischer Grünländer es ermöglichen würde Naturschutzanliegen (z.B. die Erhaltung von

Biodiversität und landschaftlicher Diversität) mit einer Verringerung von Treibhausgasemissionen im Verkehrssektors zu verbinden, und dabei gleichzeitig erneuerbare Energie aus binnenländischen Ressourcen herzustellen.

Die wichtigsten Ergebnisse der Arbeit sind:

1. Alle untersuchten Lebenszyklen für Biokraftstoffe waren Kohlenstoff- und Treibhausgas-negativ, d.h. die Lebenszyklen der Biokraftstoffe waren netto Quellen für CO_2 und Treibhausgase. Dies spiegelte die weiten Systemgrenzen wider, die für diese Studie angenommen wurden, und biogene Kohlenstoff-Emissionen sowie vorgelagerte Emissionen von Inputs in den Lebenszyklus beinhalteten. CO_2-emissionen aus Biomasse und CO_2 Gaswechsel der Grünländer zeigten den größten Einfluss auf die Bilanzen von Kohlenstoff und Treibhausgasen. Den Düngergaben zugehörige Emissionen von N_2O und CO_2 trugen wesentlich zu den gesamten Treibhausgasemissionen bei, und waren Unterscheidungsfaktor zwischen Kohlenstoff- und Treibhausgasbilanz. Deshalb zeigten die Emissionen der Düngergaben das größte Potential für eine Reduktion von Treibhausgasemissionen im Lebenszyklus von Biokraftstoffen aus Grünlandbiomasse. Die in allen Grünländern auftretende Senke für Methan hatte wenig Einfluss auf Kohlenstoff- und Treibhausgasbilanzen. Hinsichtlich Kohlenstoff- und Treibhausgasemissionen zeigte diese Studie die Wichtigkeit biogener Kohlenstoffflüsse und von N_2O Verlusten für die Bewertung von Biokraftstoffen. Wir folgern daraus, dass die Analyse und Bewertung der Lebenszyklen von Biokraftstoffen, (a) strikt auf Flüssen(fluxes) von Kohlenstoff und Treibhausgasen basieren soll, (b) einen Ansatz enthalten soll, der auf der Ebene von Treibhausgasen eine Änderung im Energiesystem quantifiziert, und, (c) eine Abschätzung von Umweltwirkungen auf Basis der Transportleistung beinhalten soll.
2. Der Nettowirkungsgrad (d.h. Quotient aus dem Energiegehalt der Produkte und der gesamten während des Lebenszyklus aufgewandten Energie) der Biokraftstoffe aus österreichischer Grünlandbiomasse war bescheiden verglichen mit international publizierten Fallstudien, was auf eine energieintensive Grünlandbewirtschaftung zurückzuführen war. Hinsichtlich des absoluten Energieertrags waren die untersuchten Biokraftstoffe vergleichbar mit anderen Biokraftstoffen der zweiten Generation.
3. In unserer Studie wurde ein Zielkonflikt für die Produktion von Biokraftstoffen deutlich, und zwar zwischen der Optimierung des Grünlandes zur Sequestrierung von Kohlenstoff und einer effizienten Energiegewinnung einerseits, und andererseits der Optimierung des Grünlandes zur effektiven Treibhausgasreduktion. Extensive Grünländer zeigten die effektivsten Treibhausgasreduktionen, wohingegen intensive Grünländer die effizienteste

Energieproduktion, die höchste Rezyklierung von Kohlenstoff und die flächenbasiert größten Einsparungen von Treibhausgasen ermöglichten. Allerdings zeigten alle untersuchten Szenarien netto Energiegewinne und, im Vergleich zu fossilen Kraftstoffen, verringerte Treibhausgasemissionen der Transportdienstleitungen.

4. Auf Ebene der Modellhöfe unterschieden sich die Technologien zur Herstellung von Biokraftstoffen hinsichtlich der Rezyklierung von Kohlenstoff, dem Einsparungspotential für Treibhausgase und der Energieeffizienz. Die Verbrennung von Biomasse zeigte die günstigste Energieeffizienz und das höchste Einsparungspotential für Treibhausgase, wohingegen das Potential für die Rezyklierung von Kohlenstoff zwischen den beiden anderen Konversionspfaden lag. Fermentierung von Lignocellulose zeigte das höchste Potential zur Rezyklierung von Kohlenstoff, während das Einsparungspotential für Treibhausgase und die Energieeffizienz im unteren Bereich der drei Technologien bilanzierten. Die Vergasung von Biomasse war für alle drei Indikatoren der am wenigsten effiziente Konversionspfad.
5. Die Produktion von Biokraftstoffen aus Grünlandbiomasse wurde für die gesamte österreichische Grünlandfläche hochgerechnet, und dabei festgestellt, dass Biokraftstoffe aus Grünlandbiomasse ein realistisches Potential aufweisen einen signifikanten Teil der österreichischen Transportleistung zu erbringen. Unsere Studie zeigte, dass die Produktion von Biokraftstoffen aus Grünlandbiomasse, vor allem für extensive Grünländer, eine aussichtsreiche Strategie zur Erhaltung der Grünlandbewirtschaftung darstellt. Zusätzlich würde, im Falle von Brachflächen oder Kulturland, eine Rekultivierung dieser Flächen als Grünland zu einer Vergrößerung der Kohlenstoffspeicher im Boden, und zu einer Erhöhung von Biodiversität auf Landschaftsebene führen.
6. Abschließend betrachtet vereinen Biokraftstoffe aus Grünlandbiomasse verschiedene Ziele die zuvor als unvereinbar galten: Verringerung von Treibhausgasemissionen, Sicherheit der Energieversorgung, ländliche Entwicklung und Naturschutz.

Figures

Abbreviations and Glossary

bio-SNG	Synthetic natural gas from biomass
BCB	Biofuel carbon balance
BCR	Biofuel carbon ratio
BGHGB	Biofuel greenhouse gas balance
BGHGR	Biofuel greenhouse gas ratio
CED	Cumulative energy demand. Refers to the sum of energy required for a certain unit of product.
CHP	Combined heat and power
CO_2e	Equivalent carbon dioxide emission: "*The amount of carbon dioxide emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a well mixed greenhouse gas or a mixture of well mixed greenhouse gases.*" (IPCC, WG1) (IPCC 2007)
Co-product	"*any of the two or more products coming from the same unit process or product system*" (DIN, ISO 14040) (DIN 2006)
ECB	Ecosystem carbon balance
ECR	Ecosystem carbon ratio
Embodied energy	Refers to the total sum of energy invested in a process during a product life cycle.
Functional unit	"*Quantified performance of a product system for use as reference unit*" (DIN, ISO 14040) (DIN 2006)
GHG:	Greenhouse gas: "*Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere*." (IPCC, WG1) (IPCC 2007)
HHV	'Higher heating value' or 'Gross calorific value'

LC-etOH	Lignocellulosic ethanol
LCA	Life Cycle Assessment "*Compilation and evaluation, of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.*" (DIN, ISO 14040) (DIN 2006)
LHV	'Lower heating value' or 'Net calorific value'
Life cycle	"*Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.*" (DIN, ISO 14040) (DIN 2006)
Mitigation	"*Technological change and substitution, that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce GHG emissions and enhance sinks.*" (IPCC, WG3) (IPCC 2007)
NGHGB	Net greenhouse gas balance
NGHGR	Net greenhouse gas ratio
pkm	passenger kilometre (calculated as vkm multiplied by a manning factor)
Upstream emission:	Emission of greenhouse gases arising outside the system boundary from production or transport of inputs to the modelled life cycle. Upstream emissions are attributed to the product which is being assessed.
System boundary	"*set of criteria specifying which unit processes are part of a product system*" (DIN, ISO 14040) (DIN 2006)
vkm	vehicle kilometre

1. Introduction

1.1 Sustainable biofuels for Austria

Society's dependence on mobility is challenged by climate change (IPCC 2007), finiteness of crude oil resources (Tsoskounogiou, Ayerides et al. 2008), and secure energy supply (Leder and Shapiro 2008), which spawned over the recent years political, economic and scientific interest in using biomass to produce 'renewable' transport fuels (Lange 2007; Bruckman 2008; Koh and Ghazoul 2008). Such 'biofuels' are heavily discussed within the scientific community (Sheehan 2009), since being put forward as strategy to stabilize greenhouse gas (GHG) emissions (Pacala and Socolow 2004).

Under current projections, Austria will miss its Kyoto target as the only EU-15 member state (EEA 2009) which will cause significant public expenditures to buy emission credits. This failure in climate change mitigation is partially attributable to CO_2 emissions from the transport sector, which soared between 1990 and 2007 by 73 %, corresponding to 28 % of the total Austrian CO_2 emissions in 2007 (Anderl, Bednar et al. 2009). To reduce GHG emissions of the transport sector, fossil fuels are blended with biodiesel and ethanol, amounting to a 4.7 % share in 2007, which is expected to rise in future (Winter 2008). In Austria biodiesel is supplied from rapeseed with overshoots for export, while ethanol is produced marginally from sugar beet, corn or wheat and mainly imported (Winter 2008).

In face of rising demand and thereby incurred biofuel imports, several aspects of first generation biofuels question their ability to sustainably fuel mobility. Their low solar energy conversion efficiency (Reiinders and Huijbregts 2007), caused by a limited exploitation of the plant's energy content (sugar, starch or oil) (Cherubini, Bird et al. 2009), is reflected in controversial energy balances (Patzek and Pimentel 2005; Farrell, Plevin et al. 2006; Hammerschlag 2006; Herrera 2006; Hill, Nelson et al. 2006; Hill 2007; Yuan, Tiller et al. 2008) questioning the energy efficiency of first generation biofuels. Additionally, recent researches showed significant GHG emissions arising from land use change (Fargione, Hill et al. 2008; Searchinger, Heimlich et al. 2008; Liska and Perrin 2009) or fertilizer inputs (Crutzen, Mosier et al. 2008) that may diminish GHG saving potentials. Furthermore, several studies have connected the use of food crops (e.g. corn, wheat or sugar beet) as biofuel feedstock to rising food prices ([Anonymous] 2007; Hill 2007; Naylor, Liska et al. 2007; Zah, Böni et al. 2007; Rosch, Skarka et al. 2009). Finally, first generation biofuels may compete for water resources (Runge and Senauer 2007; King, Holman et al. 2008; Koh and Ghazoul 2008), lead to losses of ecological services in cultural landscapes (Landis, Gardiner et al. 2008) and seriously threaten tropical forests and biodiversity (Koh and Ghazoul 2008; Eggers, Tröltzsch et al. 2009). Because of these drawbacks, first generation biofuels entail severe tradeoffs between renewable energy production and significant environmental costs.

This problematic context fostered interest in ‘second generation biofuels’, which convert the plant’s entire biomass as ‘lignocellulosic’ feedstock via several conversion platforms (e.g. thermo-chemical or biochemical) into gaseous or liquid energy carriers (Lange 2007; Cherubini, Bird et al. 2009). In future, more benign biofuels may be produced from feedstock such as perennial plants grown on degraded lands, agricultural and forestry residues, sustainably harvested wood, mixed cropping systems or waste biomass (Tilman, Socolow et al. 2009). These biofuels still need to be assessed concerning the abovementioned tradeoffs before appraisal (Firbank 2008; Petersen 2008; Robertson, Dale et al. 2008; Scharlemann and Laurance 2008; Tollefson 2008). Therefore, comprehensive energy (Costanza and Cleveland 2006; Dale 2007) and GHG metrics (Borjesson 2009; Searchinger, Hamburg et al. 2009) as well as new sustainability indicators (Piringer and Pekny 2007; Sheehan 2009) are needed for individual assessments of biofuel production chains.

Some benchmarks for a beneficial biofuel production have been discussed in the recent literature. Most important, a sustainable biofuel shall balance input and output energy in an efficient way (Davis, Anderson-Teixeira et al. 2009) while saving greenhouse gases compared to fossil fuels (Rosch, Skarka et al. 2009). Additionally, the biofuel feedstock should be non-invasive (Raghu, Anderson et al. 2006), familiar to farmers (Antizar-Ladislao and Turrion-Gomez 2008; Sanderson and Adler 2008), and allow limited (or at best, no) change in land use practice (Righelato and Spracklen 2007; Fargione, Hill et al. 2008; Groom, Gray et al. 2008; Searchinger, Hamburg et al. 2009). To be environmentally sound, biofuel will have to maintain (Firbank 2008), or even enhance biodiversity (Eggers, Tröltzsch et al. 2009; Haughton, Bond et al. 2009), should not lead to enhanced water use (King, Holman et al. 2008) and comply with sustainable agriculture (Cherubini, Bird et al. 2009). Lastly, a socially beneficial biofuel shall avoid conflicts with food production (Naylor, Liska et al. 2007) and shall be implemented in a local context (Antizar-Ladislao and Turrion-Gomez 2008). Such benchmarks will be important for the assessment of future biofuel production systems.

1.2 Permanent grassland biomass as biofuel feedstock

This work investigated the production of second generation biofuels from biomass of permanent grassland in Austria. Grassland biomass has been studied as biofuel or bioenergy feedstock, in the U.S. (Tilman, Hill et al. 2006; Mulkey, Owens et al. 2008; Adler, Sanderson et al. 2009), European (Kiesewalter, Riehl et al. 2007; Oechsner 2008; Tonn, Thumm et al. 2008; Prochnow, Heiermann et al. 2009; Rosch, Skarka et al. 2009; Wachendorf, Richter et al. 2009) and Chinese (Zhou, Xiao et al. 2009) context. Compared to conventional bioenergy crops, perennial grasslands exhibit, as a no-till system, less soil organic carbon losses (Anderson-Teixeira, Davis et al. 2009) and a higher annual net primary productivity (Gomez, Steele-King et al. 2008). Grasslands already exist as important landscape elements (Wrbka, Fink et al. 2002), therefore emissions from land use change and adaptation of farmers to new cropping systems could be avoided.

Austria's permanent grasslands are mostly linked to dairy and meat production systems (Buchgraber and Gindl 2004) and managed according to topographic, edaphic and climatic conditions (Hoppichler, Blab et al. 2002; Greif, Parizek et al. 2005) as a patchwork of plots in various management intensities (Buchgraber and Gindl 2004). Grasslands evolved over centuries by human-nature interaction on behalf of forest (Greif, Parizek et al. 2005), building up significant soil organic carbon pools, estimated to be in size of 81 Mg C ha^{-1} for intensive, and up to 119 Mg C ha^{-1} in case of extensive grasslands (Gerzabek, Strebl et al. 2005).

Grasslands provide ecological services such as biomass production, water purification, erosion control, biodiversity and aesthetics (Sala and Peruelo 1997; Greif, Parizek et al. 2005; Lindborg, Bengtsson et al. 2008). These sustained ecosystem services are contrasted by the industrialisation of Austrian agriculture since the 1950's, marked by increases in fossil energy input and machine application and a significant decline in grassland area (Krausmann, Haberl et al. 2003). Since the 1980's better income opportunities outside the agricultural sector were leading to an amplified abandonment of farms, mostly in mountainous regions unfavourable for farming (Streifeneder and Ruffini 2007). At the same time the average size of Austrian farms grew with means of cultivated area per farm amounting to 9.6 and 18.8 hectares in 1951 and 2005, respectively (BMLFUW 2008). Between 1960 and 2007 the total area of cultivated grassland in Austria retreated 39 %; extensive grassland declined 45 % and meadows in one-cut regime lost 91 % of their extent, the latter mainly because of reforestation or intensification (BMLFUW 2008). This change in landscape structure may have been detrimental for biodiversity (Helm, Hanski et al. 2006), as small land use patches with irregular boundaries and a low to intermediate disturbance regime were found to positively influence species richness (Moser, Zechmeister et al. 2002; Benton, Vickery et al. 2003). If grassland biomass would be adequately used for biofuel production, grassland management could be stabilized by additional income opportunities for farmers (Streifeneder and Ruffini 2007; Lindborg, Bengtsson et al. 2008). In that way, biofuels from permanent grassland could bring together rural development, energy security, and climate change mitigation as well as nature conservation goals.

Permanent grasslands may perform as ‘low-input high-diversity’ systems (Tilman, Hill et al. 2006), providing lignocellulosic biofuel feedstock with moderate to low fertilizer and energy inputs while still being able to provide the abovementioned ecosystem services. By a comparative life cycle approach, this work investigated intensive (high input) and extensive (moderate to low inputs) permanent grasslands as feedstock for biofuel production. We quantified carbon, GHG and energy fluxes for the complete life cycles of grassland biofuels to assess their environmental impacts. Additionally, carbon, GHG and energy ratios were calculated to compare effectiveness of land use and biofuel production chains.

In this study we specifically aimed at a better understanding of (I) carbon balances, (II) GHG saving potentials, (III) energy conversion efficiencies and, (IV) land use implications of grassland biofuels. Because results of biofuel studies diverge strongly (Davis, Anderson-Teixeira et al. 2009), this work we have based our work on the development of a transparent, consistent and accurate (Gnansounou, Dauriat et al. 2009) set of methods for the comprehensive assessment of biofuels.

2. Methods

2.1. Life-cycle approach

In the present work, methods of life cycle assessment (DIN 2006) were chosen as approach for investigating benefits and tradeoffs associated with biofuel production (Cherubini, Bird et al. 2009; Davis, Anderson-Teixeira et al. 2009). The full life cycle ('cradle to grave') was modelled for a coherent accounting of carbon, GHG and energy fluxes to assess aforementioned benchmarks for a sustainable biofuel production. Hence, modelling of scenarios encompassed agricultural phase, biorefinery phase and end use (Figure 1). Annual balances of carbon, GHG and energy inputs, as well as outputs were calculated along the functional unit of one hectare grassland. Land use efficiency and environmental footprint (carbon, GHG and energy) of transport services were evaluated with the functional unit of one vehicle kilometre travelled.

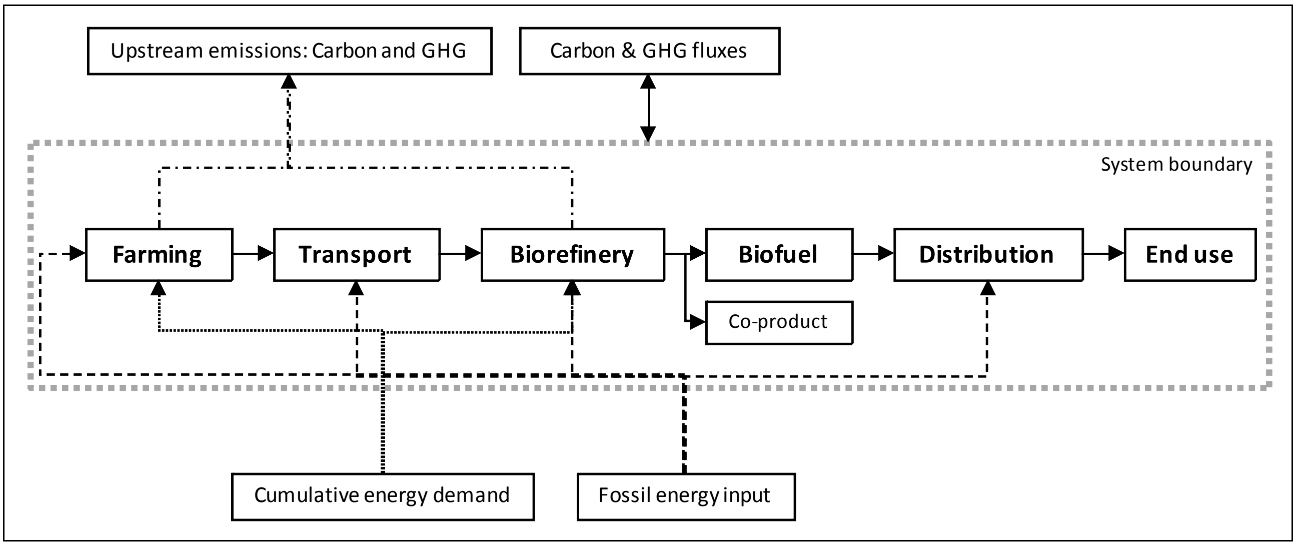

Figure 1: Overview of the modelled biofuel life cycle. Continuous lines show the biofuel production chain as well as gaseous fluxes. Upstream emissions of carbon and greenhouse gases are marked in dotted-dashed lines. Energy inputs are differentiated as fossil energy inputs (dashed lines) and cumulative energy demand (dotted lines).

2.2. Subsystems

The combination of model farms, management intensities and conversion processes allowed to calculate carbon, GHG and energy balances for the total of 27 subsystems. In the results section the subsystems are coded as follows. The capital letters M (Mountain, 1100-1300 m.a.sl.), H (Hillside, 800-1100 m.a.sl.) and V (Valley, 650-800 m.a.sl.) code the model farms equivalent to their mean elevation above sea level. The numbers 1, 2 and 3 reference grassland management intensity reflected in cutting frequency and fertilizer input. The lower case letters c (combustion of biomass for combined heat and power production (CHP)), m (gasification of biomass with subsequent methanation (bio-SNG)) and f (fermentation of lignocellulosic biomass to ethanol (LC-etOH)) mark the different biofuel conversion processes.

2.3. Delimitation

In contrast to a full scale life cycle assessment, this work did not determine environmental impacts by specific indicator methods. Rather ecological implications of a possible biofuel production from grassland biomass have been elucidated by quantifying mass and energy fluxes. Not included in this work were emissions and energy use associated with provision, use and disposal of cars. Moreover, any economic assessments of the proposed biofuel systems have been excluded.

2.4. Agricultural model

Three farms were modelled using plot based land use data from the agricultural dataset INVEKOS (anonymised and provided by the Agricultural Research and Education Centre Raumberg-Gumpenstein (Schaumberger 2009)) as a basis for the area of permanent grassland, management intensity and average slope of land use plots. Compared to the average size of permanent grassland (8.3 hectares) per Austrian farm in 2007 (Statistik-Austria 2008), the total area of permanent grassland was assumed to be 9 hectares per model farm. This area was distributed to three land use plots (one-, two- and three-cut management regime) with differences in spatial extent and average slope (Table A1).

The distribution of average slope of land use plots (Table A1) was used to discriminate farm machinery according to Austrian standard grassland management practise (BMLFUW 2008). Average weight of agricultural machinery was used to calculate cumulative energy demand as described in Ecoinvent 2.1 (Nemecek and Kägi 2007) which was then distributed over nine hectares of grassland and written off over the machinery's lifetime. A shed for farm machinery with 200 m² was modelled to calculate cumulative energy demand and embodied emission of farm buildings as described in Ecoinvent 2.1 (Nemecek and Kägi 2007) and written off over the building's lifetime. Residential buildings were excluded from the assessment.

Grassland biomass yields, referenced for elevation clusters and cutting regime, were taken from a study on alpine grasslands in Austria (Buchgraber 2000) (Table A2). Heating value and carbon content of grassland biomass was compiled from various resources (Table A3) and conservative estimates used in the calculations (Table A2). Modelling of fertilizer inputs was limited to inputs of ammonium nitrate and quantified after Austrian standard grassland management (BMLFUW 2006) for different management intensities (Table A1). Factors for upstream emissions and embodied energy for fertilizer provision were taken from Ecoinvent 2.1 (Nemecek and Kägi 2007).

Grasslands were modelled as being managed for harvesting of dry biomass (hay) on site. Thus, work processes included: grassland hauling with pasture harrow, fertilizer application, mowing, turning, and windrowing as described by Austsrian standard grassland management practise (BMLFUW 2008). Work processes were distinguished along the gradient of mean slope of land use plots according to Austrian standard grassland management practise (BMLFUW 2008) (Table A1). Baling of dry biomass and loading of bales was modelled after Ecoinvent 2.1 (Nemecek and Kägi 2007). Subsequent transport of bales to the biorefinery (Table A4) was modelled on a mass basis after Ecoinvent 2.1 (Spielmann, Bauer et al. 2007).

Emission factors (carbon and CO_2e) for diesel fuel burned in agricultural work processes were derived from Ecoinvent 2.1 (Nemecek and Kägi 2007). Net calorific value (42.8 MJ kg^{-1}) and density (0.84 kg l^{-1}) of diesel fuel were taken from Ecoinvent report number one (Frischknecht, Jungbluth et al. 2007).

2.5. Biorefinery model

Three conversion processes were chosen differing in scale, conversion efficiency, co-products, technological availability, marketability and gathering ground (Table A4).

2.5.1. Combined heat and power (CHP) via Stirling motor

Coupled ‘advanced wood combustion’ was proven a viable technology applied in more than 100 plants over Austria (Richter, Jenkins et al. 2009). We developed an analogous scenario for grassland biomass in which electricity is generated to propel electric cars while thermal excess energy can be used by a local consumer (Figure 2). Process details for a Stirling heat and power unit were taken from Ecoinvent 2.1 (Primas 2007), assuming that a Stirling unit adapted for grassland pellets would reach comparable efficiency to a woodchip based system. In accordance with market ready technologies (Stirling_DK 2009), the process described in Ecoinvent 2.1 (Primas 2007) was scaled up by a factor of ten. Energy for pelletizing of grassland biomass was modelled as three percent of biomass energy content (Finzel 2009). Emissions of carbon and greenhouse gases for pelletizing were calculated for an energy input of Austrian electricity mix (Jungbluth, Tuchschmid et al. 2007). The mass balance burning of grassland biomass in boilers and nutrient (C and N) contents of ashes were derived from a recent German study (Oechsner 2008). A shed was modelled as biorefinery building to calculate cumulative energy demand and upstream emissions as described in Ecoinvent 2.1 (Nemecek and Kägi 2007). An electrical transmission efficiency of 0.92 and a mileage of 1.2 km MJ^{-1} was modelled (Campbell, Lobell et al. 2009). Combustion of grassland biomass in small scale biomass boilers is technically feasible (Kiesewalter, Riehl et al. 2007; Rösch, Raab et al. 2007; Oechsner 2008; Tonn, Thumm et al. 2008; Prochnow, Heiermann et al. 2009; Rosch, Skarka et al. 2009) and was therefore included in this study as a decentralized biofuel scenario, which could be implemented in the short - term.

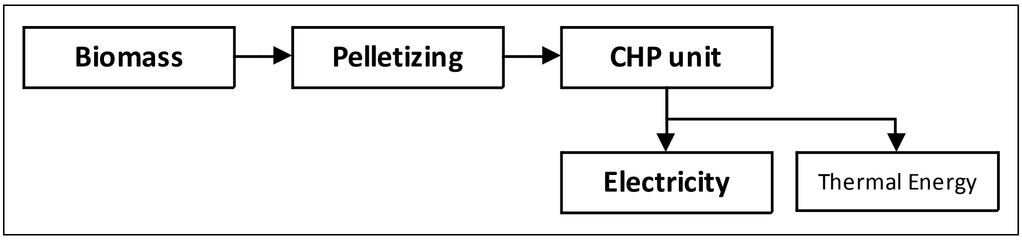

Figure 2: Flow diagram for a Stirling combined heat and power unit. Adapted from Ecoinvent 2.1 (Primas 2007)

2.5.2. Biomass to synthetic natural gas (Bio – SNG)

Production of synthetic natural gas (SNG) via gasification of biomass was put forward as a promising second generation biofuel platform (Müller-Langer, Rönsch et al. 2009). Various lignocellulosic materials can be gasified to syngas, and later be processed into different energy carriers (Jungbluth, Chudacoff et al. 2007; Lange 2007). In the present scenario, grassland biomass is gasified to syngas and subsequently processed into methane by methanation. The process was adapted from a wood chip based system as described Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007), to a system using grassland biomass as feedstock. The conversion process includes pre-treatment of feedstock, gasification, syngas cleaning and methanation (Figure 3). Cumulative energy demand as well as emissions from the gasification facility and machinery were derived Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007) and scaled down by a factor of ten. Because of the higher heating value of grassland biomass compared to wood (Table A3), and possible process optimization, the present calculation can be interpreted as conservative estimate for this biofuel pathway. A first bio-SNG demonstration plant fed by wood was recently opened in Güssing, Austria and perennial grassland biomass is expected to be an important feedstock for this technology (Müller-Langer, Rönsch et al. 2009). The scenario for bio-SNG production can be interpreted as medium-term biofuel scenario.

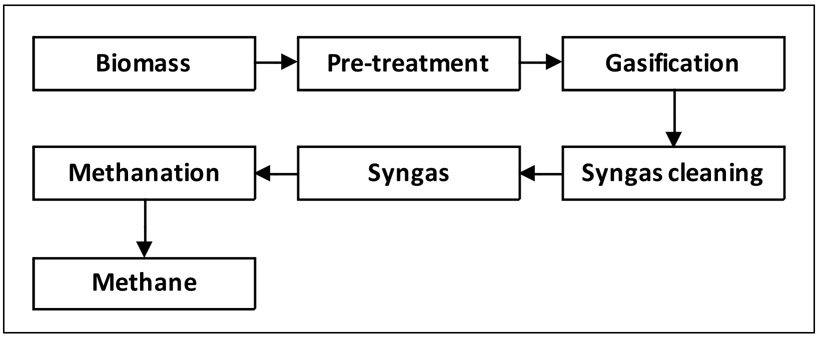

Figure 3: Flow diagram for the production of bio-SNG. Simplified after Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007).

2.5.3. Fermentation of lignocellulosic feedstock to ethanol (LC-etOH)

Lignocellulosic ethanol has been proposed as a promising pathway for biofuel production, as technical performance and energy conversion efficiency are expected to increase in the medium- to long-term (Hamelinck, van Hooijdonk et al. 2005). Carbon and energy balances of the conversion process were derived from a system using corn stover as feedstock for ethanol fermentation (Sheehan, Aden et al. 2003). This publication describes a process with pre-treatment by a diluted acid, assuming a 50% increase in yield because of improved cellulose-hydrolysing enzymes and genetically modified sugar-fermenting microorganisms (Figure 4). Electricity is produced as a co-product by burning the lignin rich conversion residues. Nutrient content of ashes was derived from a recent German study (Oechsner 2008). Factors for cumulative energy demand and upstream emissions of biorefinery machinery and biorefinery building capital were taken from Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007). The assessment of energy requirements and emissions for upstream production of enzymes and chemical inputs was omitted due to lack of data. Because the reference for cellulosic ethanol fermentation (Sheehan, Aden et al. 2003) assumes a more efficient fermentation process than is reached on an industrial scale today, and cellulosic ethanol technology is still far from mature (Wyman 2007), this lignocellulosic ethanol can be interpreted as a medium- to long-term biofuel scenario.

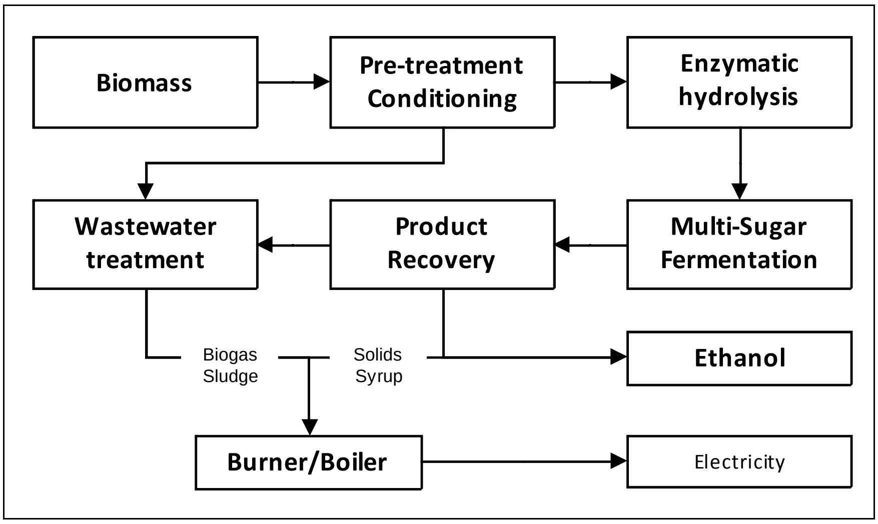

Figure 4: Flow diagram for fermentation of lignocellulosic biomass to ethanol. Simplified after Sheehan et. al. (Sheehan, Aden et al. 2003).

2.6. End use

For the distribution of energy carriers from biorefinery to filling stations, different assumptions were made depending on biofuel conversion process. Electricity generated in the Stirling co-generation process was assumed to be fed directly into electric cars or an existing electrical grid and subsequently used for electrical mobility. Methane and ethanol were assumed to be transported for 200 kilometres to a filling station. Emission factors for the transported masses were taken from Ecoinvent 2.1 (Spielmann, Bauer et al. 2007). To calculate vehicle kilometres travelled per unit of land, the energy content (LHV) of the biofuel product was divided by mileages of 1.2 km MJ^{-1} (Campbell, Lobell et al. 2009) in case of electric mobility and 0.45 km MJ^{-1} (Winter 2009) in case of cars fuelled with bio-SNG or ethanol. Carbon-dioxide emissions of biofuel end use in cars were modelled from the carbon content of the biofuel. Other greenhouse gases emitted during biofuel combustion were neglected as carbon-dioxide is the major contributor for global warming impact of transport services. Around 95 % of the total global warming potential of selected fuels from the Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007) database were found to be attributable to carbon-dioxide emissions.

2.7. Carbon fluxes

2.7.1. Ecosystem carbon balance (ECB)

The stability of soil organic carbon stocks is an important issue when assessing possible biofuel pathways (Cherubini, Bird et al. 2009) but life-cycle analyses rarely include accumulation or depletion of soil organic carbon stocks (Anderson-Teixeira, Davis et al. 2009). In the present model, the balance between carbon inputs and outputs of the grasslands was assumed to be in equilibrium as grasslands are since the late middle ages a traditional and stable land use in alpine regions of Austria (Greif, Parizek et al. 2005). Therefore an explicit sequestration bonus (Johnson 2009) was modelled as CO_2 flux ($F(CO_2)$) for the grasslands. Year to year variability, as well as climate change effects on the carbon balance of grasslands (Anderson-Teixeira, Davis et al. 2009) were not assessed in the present work.

The *'ecosystem carbon balance'* (Chapin, Woodwell et al. 2006) included below standing fluxes [kg C ha^{-1} y^{-1}]:

Ecosystem carbon balance = $F(CO_2)$ + $F(CH_4)$ + F(POC) + F(DOC)

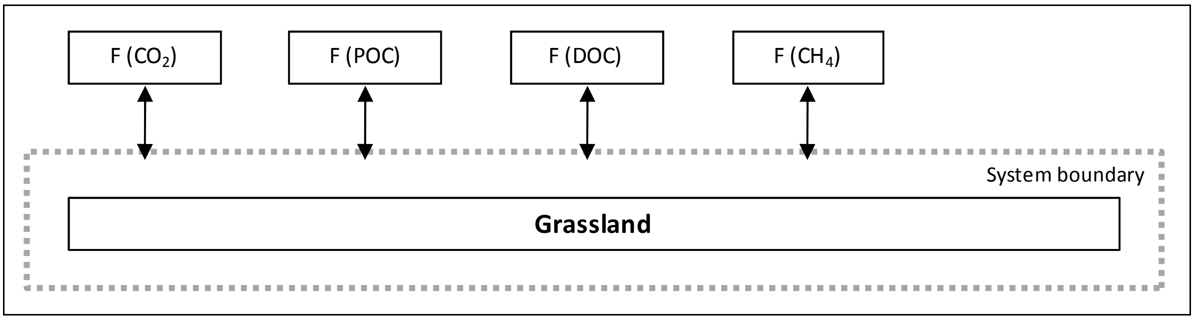

Figure 5: Fluxes constituting the ecosystem carbon balance.

Carbon sources (inputs to atmosphere and hydrosphere):

F(POC)	Flux of particular organic carbon, calculated as the sum of carbon exported from the grassland in form of harvest (C(harvest)) or returned as residues (C(residues)).
F(DOC)	Flux of dissolved organic carbon, either leached out from the grassland soils or gained by atmospheric deposition (neglected in this work). The annual rate of DOC leaching in grassland subsystems was modelled according to (Klumpp, Soussana et al. 2007) with gradients following management intensity and slope (Table A5).

Carbon sinks (atmospheric outputs):

$F(CO_2)$ — The net CO2 flux of the grassland was modelled as net uptake of CO2 according to net ecosystem exchange of CO2 in comparable grasslands (Ammann, Flechard et al. 2007) (Gilmanov, Soussana et al. 2007). The CO2 flux was set between -140 to -370 kg CO2-C ha-1 y-1 depending on grassland productivity, elevation and fertilizer input (Table A6). Thereby the grasslands were modelled to compensate for carbon exported as harvest and exhibit more or less stable soil organic carbon pools.

$F(CH_4)$ — The annual flux of methane oxidized by the grassland. Compacted soil and high fertilizer inputs may reduce activity of methane oxidizing microorganisms (Boeckx and Van Cleemput 2001). Therefore, differences in methane oxidizing activity were modelled, with values for methane uptake by grasslands ranging from 1.5 to 2.5 kg CH_4_C ha^{-1} y^{-1} (Table A7).

2.7.2. Biofuel carbon balance (BCB)

Biofuels are often branded as per se '*carbon neutral*' as the carbon released during combustion of the fuel has been sequestered during biomass growth (Mathews 2008; Johnson 2009). Because of that reason, life cycle assessments often exclude a dedicated balance of biogenic carbon fluxes (Guinee, Heijungs et al. 2009). However, this may be misleading as biomass losses (which are subsequently respired to the atmosphere) and emissions from biomass combustion, cannot be negated as fluxes of greenhouse gases (Searchinger, Hamburg et al. 2009). Additionally, carbon emissions from land management, transports and provision of auxiliaries can be significant (Adler, Del Grosso et al. 2007; Zah, Böni et al. 2007; Cherubini, Bird et al. 2009). Therefore the biofuel carbon balance presented here followed a comprehensive approach (Cherubini, Bird et al. 2009; Johnson 2009) with wide system boundaries. The biofuel carbon balance is negative for carbon sinks (fluxes which fix carbon from the atmosphere) and positive for carbon sources (fluxes which emit carbon to the atmosphere). The fluxes are distinguished by capital letters, with F standing for ecosystem fluxes and C marking anthropogenic fluxes occurring during the biofuel life cycle. In the biofuel carbon balance, the flux of carbon exported from the ecosystem (F(POC)) is split into the fluxes C(loss harvest), C(loss baling) and C(biofuel emissions).

The biofuel carbon balance contained the following fluxes [kg C ha^{-1} y^{-1}]:

Biofuel carbon balance = $\mathbf{F(CO_2) + F(CH_4) + C(residues) + F(DOC) + C(farm) + C(machinery) + C(fertilizer) + C(management) + C(loss\ harvest) + C(baling) + C(loss\ baling) + C(biorefinery) + C(energy\ input) + C(biofuel\ emission) + C(distribution)}$

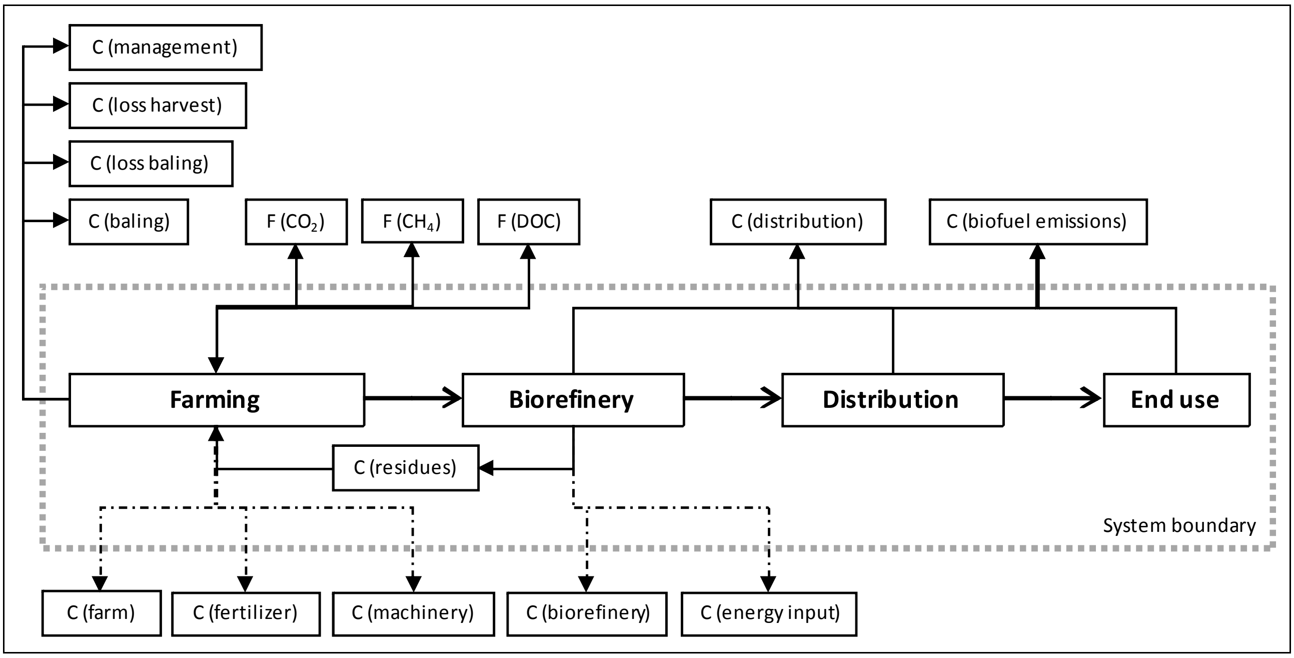

Figure 6: Schematic representation of the modelled biofuel carbon balance. The mass flow of biomass to biofuel is shown in thick continuous lines. Environmental fluxes are shown in continuous lines with arrows in both directions. Upstream emissions are marked in dashed-dotted lines. Direct gaseous emissions are labelled by continuous lines. Fossil fuel inputs to the system are not depicted here for matter of clarity.

Carbon sources (atmospheric inputs, positive):

F(DOC)	Dissolved organic carbon leached out of the grassland. ('Ecosystem carbon balance')
C(farm)	Carbon emissions from construction of farm buildings ('Agricultural model'). Carbon emissions were distributed over the grassland area and written off over the building's lifetime.
C(machinery)	Upstream carbon emissions from production and provision of farm machinery. Carbon emissions were distributed over the grassland area and written off over the machinery's lifetime.

C(fertilizer)	Upstream carbon emissions from production and provision of mineral fertilizer.
C(management)	Carbon emissions from burning of diesel fuel during grassland management.
C(loss harvest)	Portion of carbon lost during the harvest of biomass which was assumed to be fully respired to the atmosphere as CO_2.
C(baling)	Carbon emissions from machine work for baling and transport of biomass.
C(loss baling)	Portion of carbon lost during baling of biomass on the field and transport to biorefinery. This carbon was assumed to be fully respired to the atmosphere as CO_2.
C(biorefinery)	Carbon emitted during production and provision of biorefinery machinery and building stock.
C(energy input)	Carbon emissions from production of external energy used during biofuel conversion. Emission factors for the Austrian electricity mix are taken from (Jungbluth, Tuchschmid et al. 2007).
C(biofuel emission)	Carbon emitted from combustion of biomass during processing and enc use of the biofuel.
C(distribution)	Carbon emitted during transport of biofuels from biorefinery to filling station.

Carbon sinks (atmospheric outputs, negative):

$F(CO_2)$	Carbon flux of the grassland ('Ecosystem carbon balance')
$F(CH_4)$	Carbon in the methane flux of the grassland ('Ecosystem carbon balance')
C(residues)	Carbon in residues of the biofuel conversion processes which are returned to the grasslands.

2.8. GHG fluxes

2.8.1. Biofuel GHG balance (BGHGB)

The biofuel GHG balance follows the same system boundaries as the biofuel carbon balance, allowing a comprehensive assessment of GHG fluxes (Adler, Del Grosso et al. 2007; Searchinger, Hamburg et al. 2009). The GHG sink, accounted for as negative emission, is constituted by fluxes which sequester CO_2e from the atmosphere. The GHG source, accounted for positively, contains fluxes which emit CO_2e into the atmosphere. The fluxes are distinguished by capital letters, with F, denoting ecosystem fluxes, CO_2, marking fluxes of CO_2 arising from biomass, and CO_2e, referencing fluxes which contain greenhouse gases such as N_2O, CH_4, and CO_2.

The biofuel GHG balance includes the following fluxes [MG CO_2e ha^{-1} y^{-1}].

Biofuel GHG balance = CO_2e(farm) + CO_2e(machinery) + CO_2e(fertilizer) + CO_2e(N_2O) + CO_2e(management) + CO_2(loss harvest) + CO_2e(baling)+ CO_2(loss baling) + CO_2e(biorefinery) + CO_2e(energy input) + CO_2e (biofuel emissions) + CO_2e (distribution) + F(CO_2) + F(CH_4)

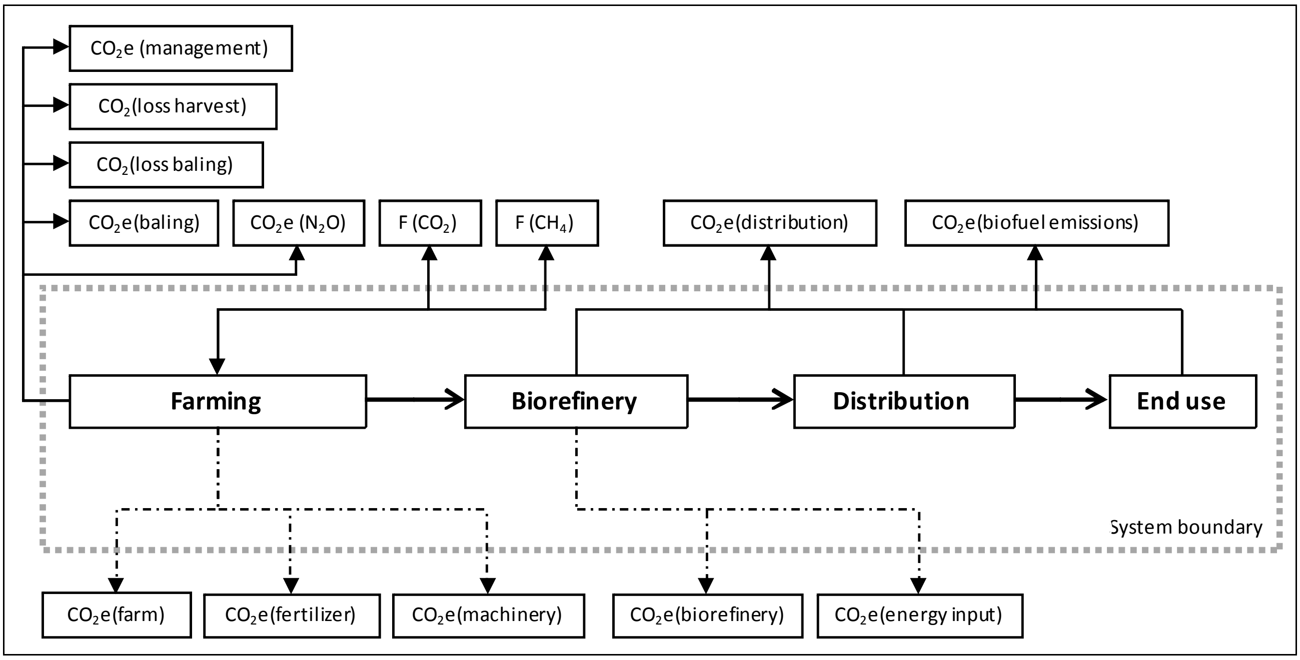

Figure 7: Schematic representation of the modelled biofuel GHG balance. The mass flow of biomass to biofuel is shown in thick continuous lines. Environmental fluxes are shown in continuous lines with arrows in both directions. Upstream emissions are marked in dashed-dotted lines, and direct gaseous emissions are labelled by continuous lines. Fossil fuel inputs to the system are not depicted here for matter of clarity.

GHG sources (atmospheric inputs in CO_2-equivalents, positive):

CO_2e (farm)	Emissions from the construction of farm building stock. Emissions were distributed over the grassland area and written off over the building's lifetime.
CO_2e (machinery)	Emissions from the provision of farm machinery. Emissions were distributed over the grassland area and written off over the machinery's lifetime.
CO_2e (fertilizer)	Upstream emissions from mineral fertilizer production and provision
CO_2e (N_2O)	Direct emissions of N_2O from fertilizer inputs into the grasslands. An emission factor for temperate grasslands of 0.01% of nitrogen fertilizer input for direct N_2O emissions arising (Klein, Novoa et al. 2008) was used and calculated into CO_2e by a factor of 298 (IPCC 2007). Indirect emissions of N_2O by offsite denitrification of NO_3 were neglected.
CO_2e (management)	Emissions from diesel use in agricultural work processes.
CO_2 (loss harvest)	Carbon lost during harvest of biomass which was assumed to be fully respired.
CO_2e (baling)	Diesel emissions during baling and transport of biomass from field to biorefinery.
CO_2 (loss baling)	Carbon lost during baling and transport of the biomass which was assumed to be fully respired.
CO_2e (biorefinery)	Emissions caused by provision of biorefinery buildings and machinery.
CO_2e (energy input)	Emissions due to the use of external energy (electricity) to power the biofuel production process. Emission factors for the Austrian electricity mix are taken from (Jungbluth, Tuchschmid et al. 2007).
CO_2e (biofuel emissions)	Emissions during conversion and combustion of the biofuel.
CO_2e (distribution)	Emissions during distribution of the biofuel from biorefinery to well.

GHG sinks (atmospheric outputs in CO_2-equivalents, negative):

F(CO_2)	The annual carbon dioxide flux of the grassland ('Ecosystem carbon balance').
F(CH_4)	The annual methane flux of the grassland ('Ecosystem carbon balance') was calculated as CO_2e with a factor of 25 (IPCC 2007).

2.8.2. Avoided Emissions compared to the reference scenario- Net GHG balance (NGHGB)

In a change oriented approach, the net GHG balance was calculated to elucidate possibilities of avoiding GHG emissions by switching from fossil to renewable fuels. These 'avoided emissions' are accounted for as emission bonus (negative emissions) in the net GHG balance (Adler, Del Grosso et al. 2007). Subsystems exhibiting negative values for NGHGB successfully reduce GHG emissions compared to today's reference situation, but are not necessarily GHG neutral or negative.

The net GHG balance contains the following fluxes [MG CO_2e ha^{-1} y^{-1}]:

Net GHG balance = BGHGB + CO_2e (dg) +CO_2e(do) + CO_2e(de)

GHG emissions avoided (atmospheric outputs in CO_2-equivalents, negative):

CO_2e (dg)	GHG savings from substitution of fossil fuels (dg = displacement of gasoline). As reference scenario for today's transport service, emissions of an 'Euro 5 petrol car' were taken from Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007).
CO_2e (do)	GHG savings from displacing oil (do = displacement of oil), by co-product heat from the heat and power cogeneration process. One tenth of the heat energy was modelled as ambient loss. The reference scenario for heat energy replaced was light oil combustion for heating as common for a quarter of heating energy in Austria in 2005 (AEA 2006). Emissions were modelled as described in Ecoinvent 2.1 (Jungbluth 2007).
CO_2e (de)	GHG savings from displacing electricity (de = displacement of electricity) from the current Austrian electricity mix (Jungbluth,

Tuchschmid et al. 2007) by co-produced electricity from combustion of lignin-rich residues in the ethanol fermentation process (Sheehan, Aden et al. 2003).

2.9. *Energy fluxes*

2.9.1. Net energy balance (NEB)

The 'net energy balance' (Hammerschlag 2006; Tilman, Hill et al. 2006; Schmer, Vogel et al. 2008) was calculated along the same system boundaries as biofuel carbon balance and biofuel GHG balance. Energy inputs were calculated for all energy consuming processes such as grassland management, biomass transport, biofuel conversion and distribution as well as upstream energy used for auxiliaries. The main output of the biofuel life cycles was the energy captured in the biofuel. Two balances were calculated to differentiate biofuel life cycles without co-products (Net Energy Balance (NEB)) and with thermal or electrical energy as co-products (Net Energy Balance with co-products (NEB_CP)).

The net energy balance contains the following fluxes [GJ ha^{-1} y^{-1}]:

Net energy balance = E(biofuel) – [E(farm) + E(machinery) + E(fertilizer) + E(management) + E(baling) + E(biorefinery) + E(energy input) + E(distribution)]

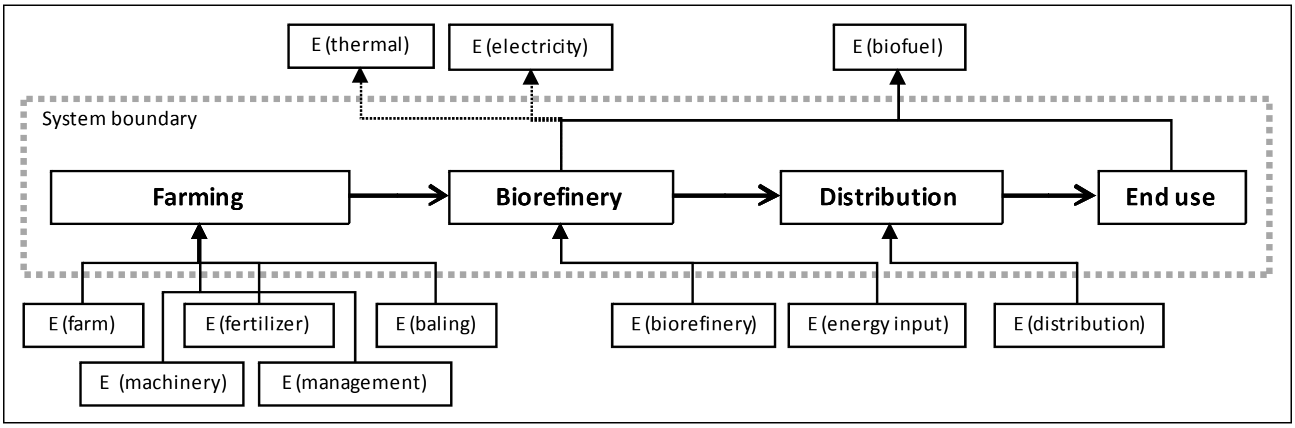

Figure 8: Schematic representation of the modelled net energy balance including co-products. The energy flow of biomass to biofuel is shown in thick continuous lines. Energy inputs and outputs are distinguished by direction of arrows. Co-products are distinguished by dotted lines.

2.9.2. Net energy balance including co-products (NEB_CP)

The net energy balance including co-products (Figure 8) contains the following fluxes [GJ ha^{-1} y^{-1}]:

Net energy balance including co-products = NEB+ E(heat) + E(electricity)

Energy lost during biofuel life cycle (input):

E(farm)	Cumulative energy demand for construction of farm buildings.
E(machinery)	Cumulative energy demand for provision of farm machinery.
E(fertilizer)	Cumulative energy demand for provision of mineral fertilizer.
E(management)	Energy used in grassland management as diesel fuel.
E(baling)	Energy used for baling and transport of biomass from field to biorefinery.
E(biorefinery)	Cumulative energy demand of biorefinery buildings and machinery.
E(energy input)	External electric energy input for biofuel production.
E(distribution)	Energy used for transport of biofuel to well.

Energy gained during biofuel life cycle (outputs):

E(biofuel)	Energy content (lower heating value) of the biofuels produced.
E(heat)	Heat energy gained as co-product in the combustion scenarios.
E(electricity)	Electricity produced as co-product in the fermentation scenarios.

3. Results

3.1. Carbon fluxes

3.1.1. Ecosystem carbon balance (ECB)

Across all subsystems, the ECB exhibited a tendency to accumulate carbon with a mean value of minus 7.8 kg C ha^{-1} y^{-1} (median – 1.9). Values for ECB were ranging from a carbon accumulation of 56 kg C ha^{-1}y^{-1} in the subsystem hillside/three-cut/fermentation to a carbon loss of about 23 kg C ha^{-1} y^{-1} in the subsystem valley/three-cut/gasification.

A one-way ANOVA showed no significant (95 %) differences within means of ECB for the factors elevation ($p = 0.1203$), conversion process ($p = 0.3798$) and management intensity ($p = 0.0914$).

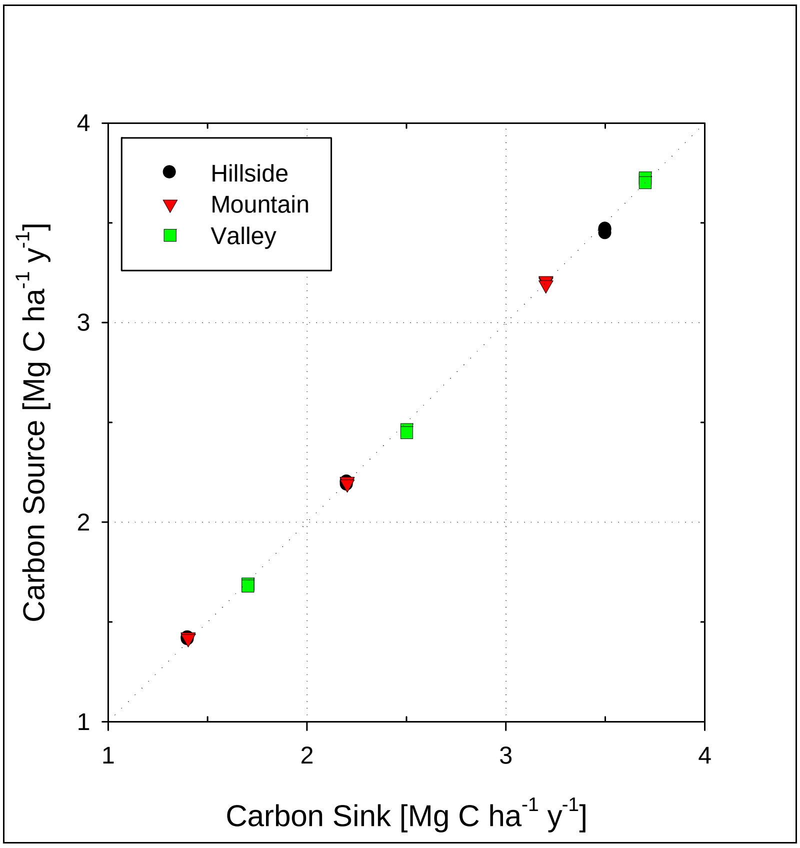

Figure 9: Carbon sinks and sources constituting the ecosystem carbon balance (ECB). Carbon sinks, fixing carbon from the atmosphere, are plotted against carbon sources, emitting carbon to the atmosphere. Values for ECB are marked with dots (hillside subsystems between 800 and 1100 a.m.s.l.); triangles (mountain subsystem between 1100 and 1300 a.m.s.l.) and squares (valley subsystems between 650 and 800 a.m.s.l.).

3.1.2. Ecosystem carbon ratio (ECR)

The ‘ecosystem carbon ratio’ was calculated as ratio between ecosystem carbon sink and source. An ecosystem carbon ratio in excess of one implies a carbon sink for a subsystem, thus an accumulation of carbon in the soil organic carbon pool.

Ecosystem carbon ratios were found around one for all subsystems. ECR exhibited for all subsystems a mean of 1.002 (± 0.010) with values ranging between 0.98 and 1.02, indicating a maximal change (accumulation or depletion) in soil organic carbon pools of two percent per year.

A one-way ANOVA showed significant (95%) differences within means of ECR for the factors elevation ($p = 0.0351$) and intensity ($p = 0.0351$) but not conversion process ($p = 0.4157$).

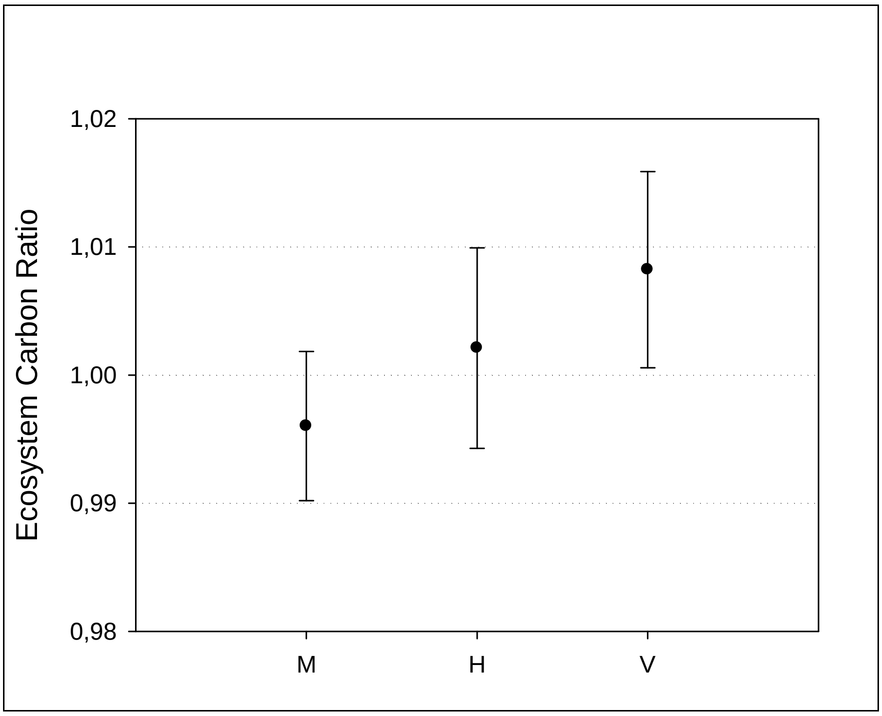

Figure 10: Ecosystem carbon ratios grouped for the factor elevation. Capital letters code mean elevation above sea level (M = mountain, H = hillside and V = valley). Grasslands in lower elevations accumulated more carbon than grasslands in higher altitudes, which tended to lose carbon. Whiskers show 95 % confidence intervals.

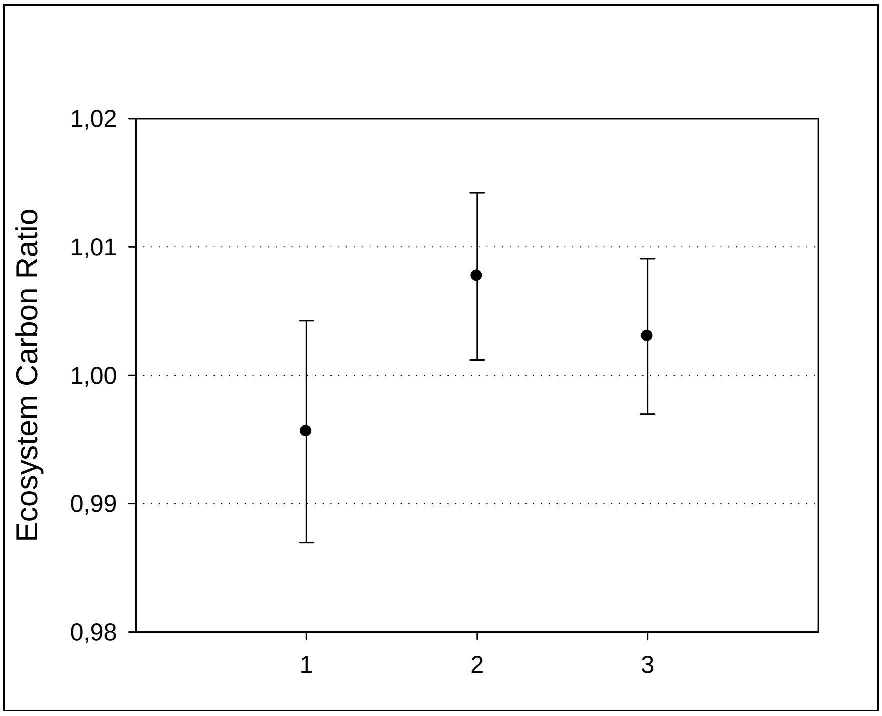

Figure 11: Ecosystem carbon ratios grouped for the factor management intensity. Numbers code management intensity. Subsystems with a one-cut management regime exhibited a greater tendency for carbon losses than grasslands with two- or three-cut management regimes. The on average greatest accumulation of carbon was found for two-cut mowing regimes. Three-cut subsystems returned a slightly lower mean than two-cut subsystems. Whiskers show 95 % confidence intervals.

3.1.3. Biofuel carbon balance (BCB)

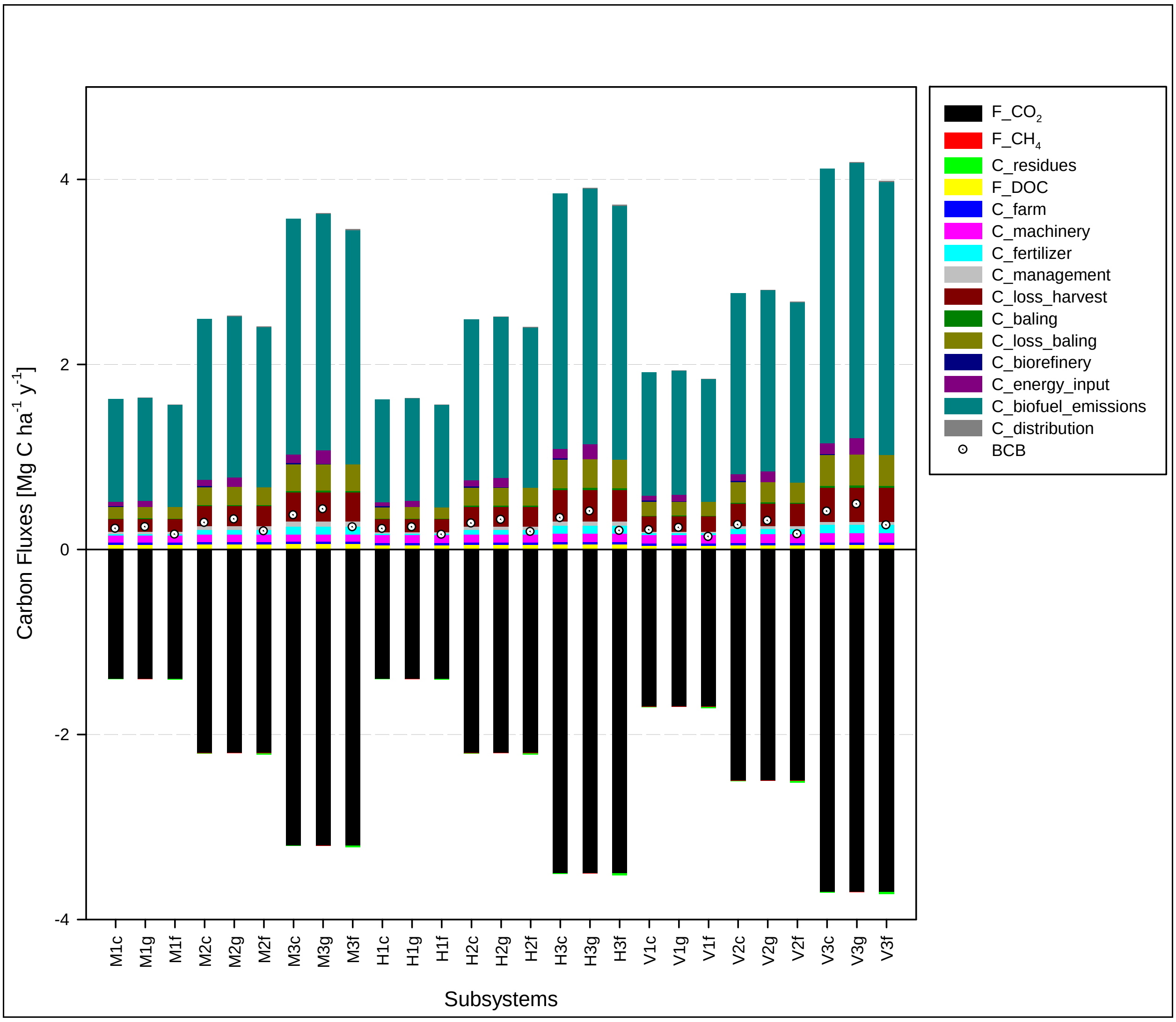

Figure 12: Biofuel carbon balance with constituent carbon fluxes. Dots indicate biofuel carbon balance, calculated as sum of carbon inputs and outputs. Capital letters signify elevation (M = mountain, H = hillside, V = valley), numbers code management intensity (1 = one-cut, 2 = two-cut, 3 = three-cut) and lowercase letters mark conversion processes (c = combustion (CHP), G = gasification (bio-SNG), f = fermentation (LC-etOH)).

All subsystems were found to be net carbon sources with a mean value for BCB of 0.27 Mg C ha^{-1} y^{-1} (± 0.09). Values for BCB range from 0.13 Mg C ha^{-1} y^{-1} in the subsystem valley/one-cut/fermentation to a maximal value of 0.49 Mg C ha^{-1} y^{-1} in the subsystem valley/three-cut/gasification.

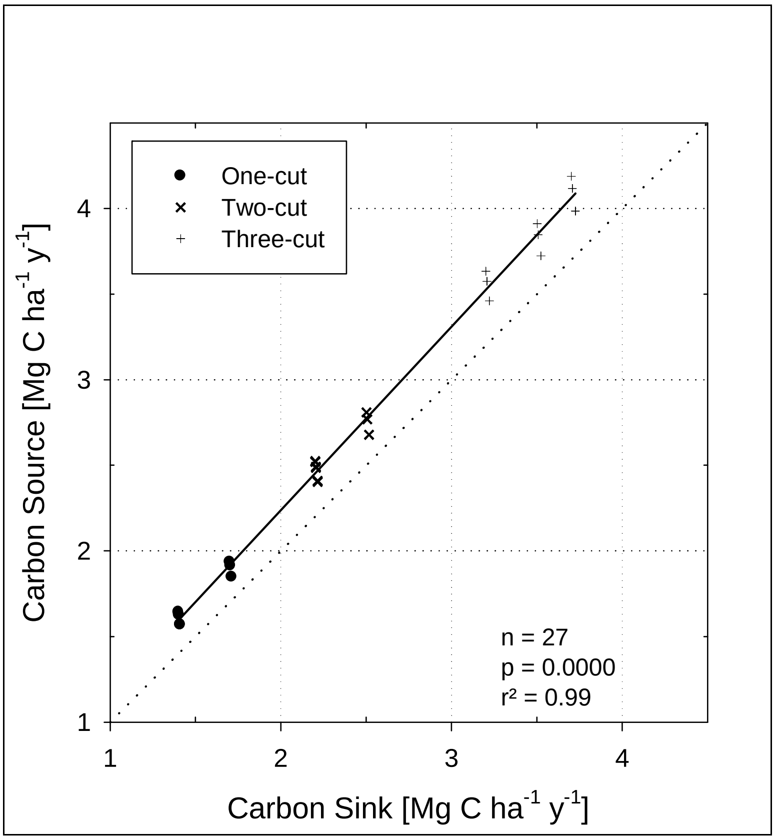

Figure 13: Biofuel carbon sinks and sources for the factor management intensity. The carbon sink is plotted against the carbon source. Values are differentiated according to management intensity with values for one-cut subsystems plotted as dots, for two-cut subsystem plotted as Xs and values for three-cut subsystems plotted as crosshairs. A regression model shows biofuel carbon sources as function of carbon sinks (BCB_source = 0.094 + 1.07 * BCB_sink).

The biofuel carbon gain was found to mainly consist of net CO_2 exchange (F_CO_2) of grasslands (mean of 99.6 %). Carbon emissions from biofuel burning (C_biofuel emissions) are the biggest carbon source with about 70 % of the total carbon source (Table 1). Carbon fluxes caused by harvest, baling and transport (C_loss-harvest and C_loss-baling) as well as from provision of agricultural machinery (C_machinery) are an order of magnitude smaller but add up to about 30% of the total carbon source.

A one-way ANOVA showed highly significant (99%) differences within means of BCB for the factors management intensity ($p = 0.0006$) and conversion process ($p = 0.0008$), while the factor elevation ($p = 0.9486$) had no significant influence on means of BCB.

Table 1: Relative size of carbon fluxes compared to the total biofuel carbon source.

Flux	% of Carbon source (mean)	SD
C_biofuel emissions	70.6	± 1.7
C_loss harvest	8.7	± 0.2
C_loss baling	7.9	± 0.2
C_machinery	3.5	± 1.1
C_energy input	2.2	± 1.7
F_DOC	2.0	± 0.6
C_fertilizer	1.8	± 0.6
C_farm	1.1	± 0.4

Note: The percentage of the single carbon fluxes is a fraction of the carbon flux to the total carbon source. Numbers show mean values across all subsystems with standard deviations.

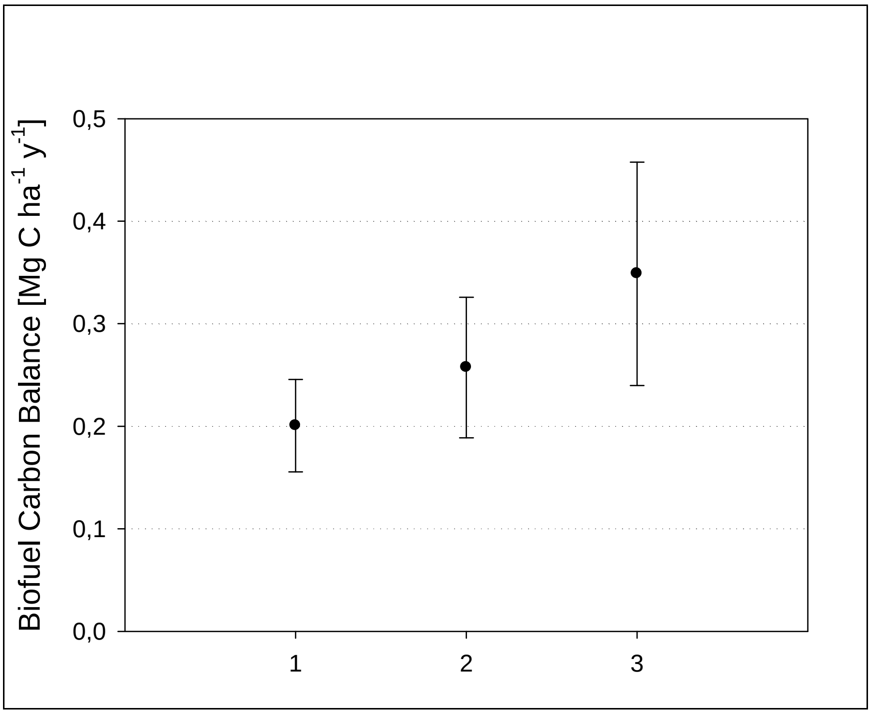

Figure 14: Biofuel carbon balances grouped for the factor management intensity. Numbers on the x-axis code management intensity. BCB means of one-cut subsystems emitted less carbon than three-cut subsystems. Whiskers show 99 % confidence intervals.

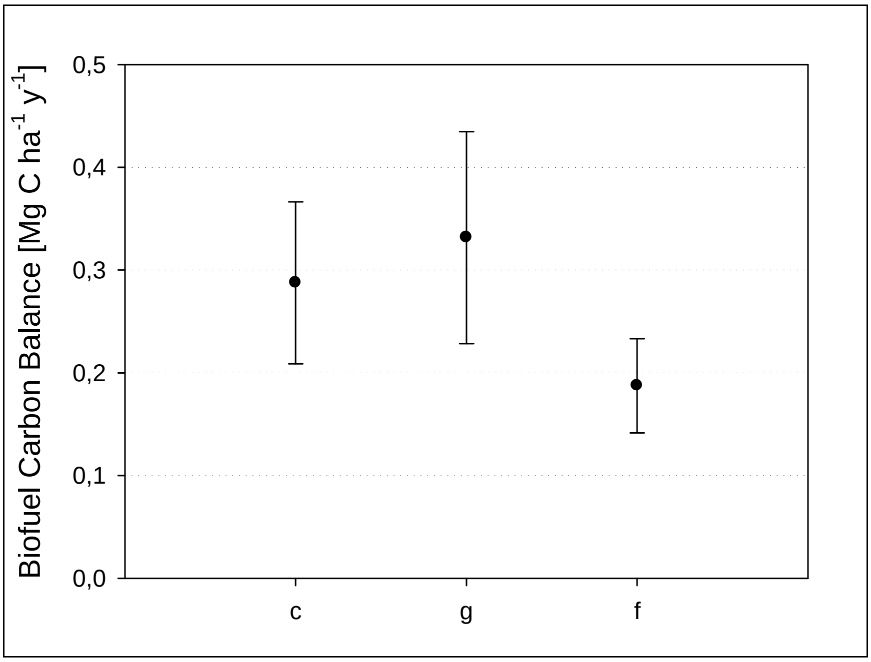

Figure 15: Biofuel carbon balances grouped for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Fermentation subsystems emitted less carbon than combustion and gasification subsystems. Gasification subsystems returned the highest values for BCB. Whiskers show 99 % confidence intervals.

3.1.4. Biofuel carbon ratio (BCR)

The 'biofuel carbon ratio' was calculated as ratio of biofuel carbon sink to source. Ratios higher than one would signify a net carbon sink, thus a 'carbon-negative' life cycle.

For all investigated subsystems BCR was smaller than one, indicating all subsystems as net carbon sources. Average BCR amounted to 0.9 (± 0.03) with the maximum BCR of 0.95 in the subsystem hillside/three-cut/fermentation, signifying that five percent of total carbon emitted could not be fixed during the biofuel life cycle. Minimal BCR amounted to 0.85 in the subsystem mountain/one-cut/gasification, demonstrating that 15% of carbon inputs could not be sequestered.

A one-way ANOVA showed a significant (95 %) difference within means of BCR for the factor conversion process ($p = 0.0000$) but not for the factors management intensity ($p = 0.067$) and elevation ($p = 0.3869$).

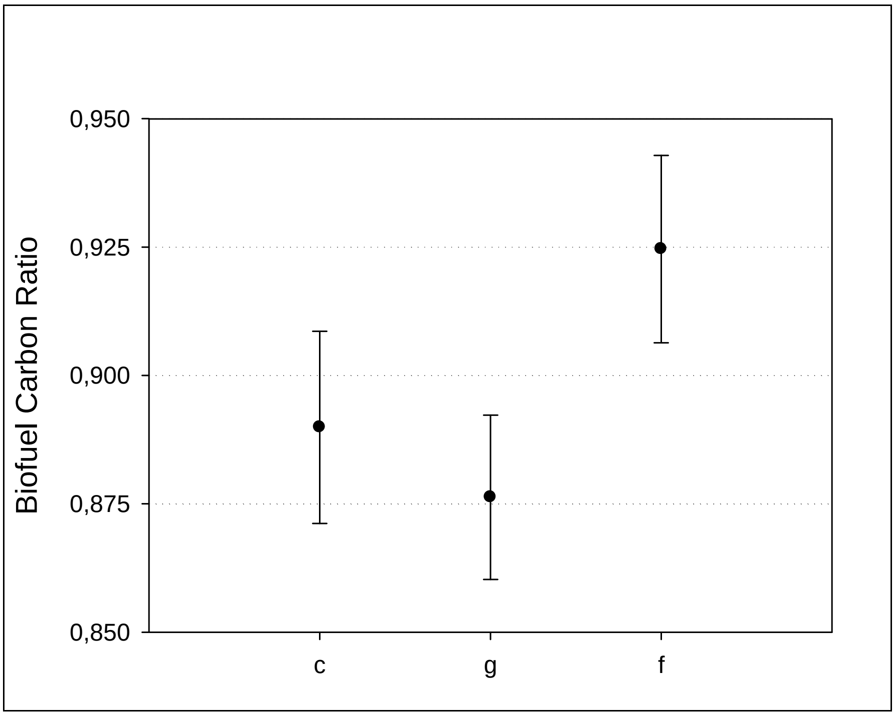

Figure 16: Biofuel carbon ratios for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). The lowest means of BCR were found for gasification subsystems. Combustion pathways exhibited a slightly higher mean for BCR. The highest values for BCR were found for fermentation subsystems. Whiskers show 99 % confidence intervals.

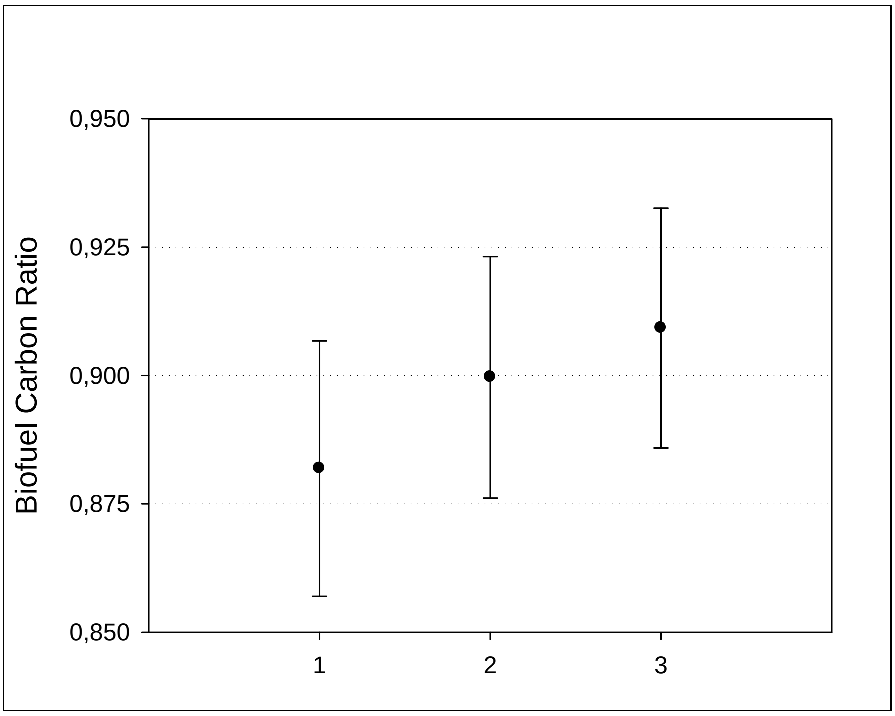

Figure 17: Biofuel carbon ratios for the factor management intensity. Numbers code management intensity. Means of BCR differentiated along the gradient of management intensity. One-cut subsystem exhibited the biggest and three-cut subsystems the smallest carbon sources. Whiskers show 99 % confidence intervals.

3.2. GHG fluxes

3.2.1. Biofuel GHG balance (BGHGB)

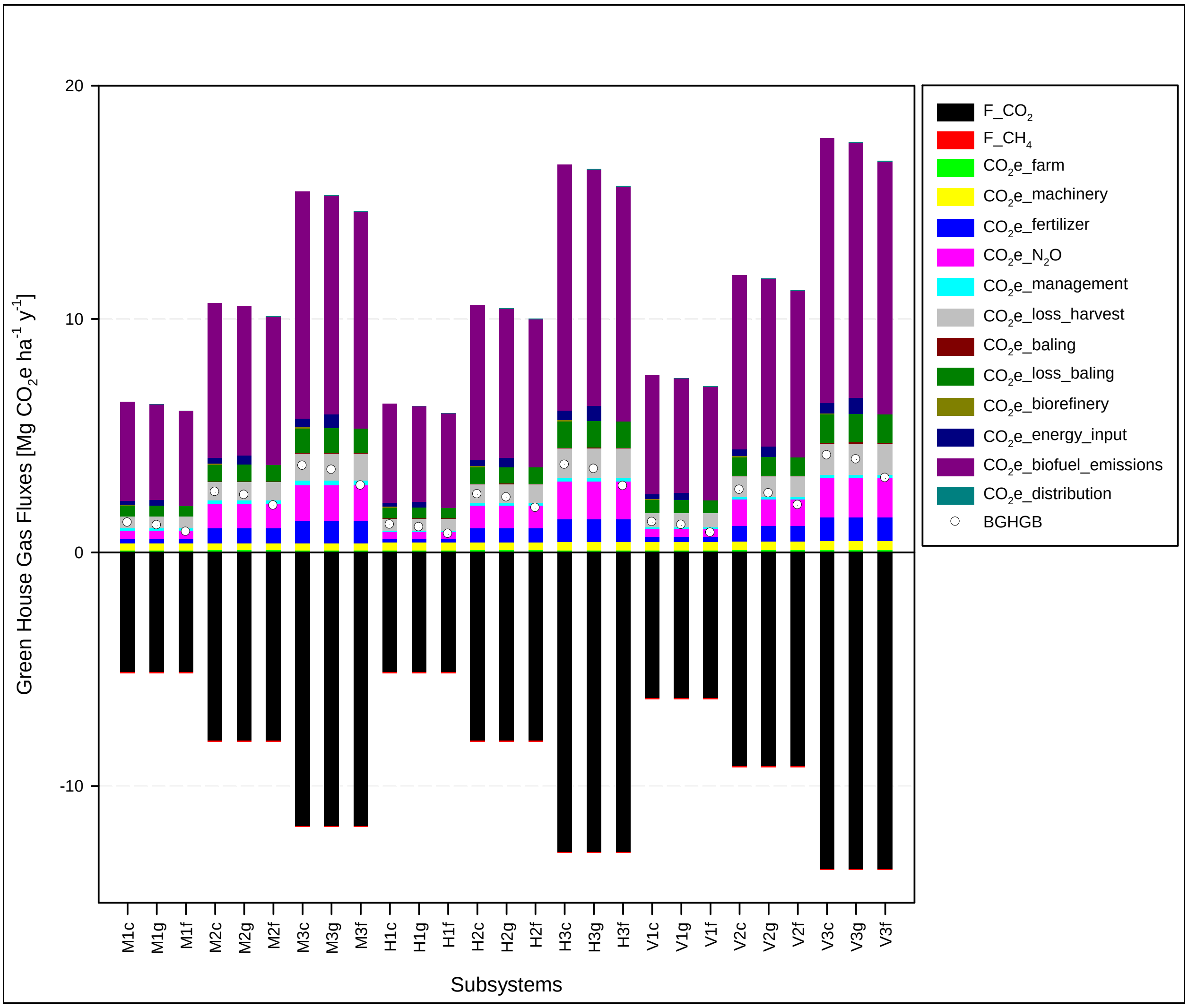

Figure 18: Biofuel GHG balance with constituent GHG fluxes. Dots indicate BGHGB, calculated as sum of Biofuel GHG inputs and outputs. Subsystems are coded according to mean elevation above sea level (M = mountain, H = hillside, V = valley), management intensity (1 = one-cut, 2 = two-cut, 3 = three-cut) and conversion processes (c = combustion (CHP), g = gasification (bio-SNG), f = fermentation (LC-etOH).

All subsystems were found to be net greenhouse gas sources, reflected in a mean value for BGHGB of 2.3 Mg CO_2e ha^{-1} y^{-1} (median 2.5). The subsystem with least CO_2e-emissions was hillside/one-cut/fermentation with 0.8 Mg CO_2e ha^{-1} y^{-1}, contrasted by the subsystem valley/three-cut/combustion with the biggest GHG source of 4.2 Mg CO_2e ha^{-1} y^{-1}.

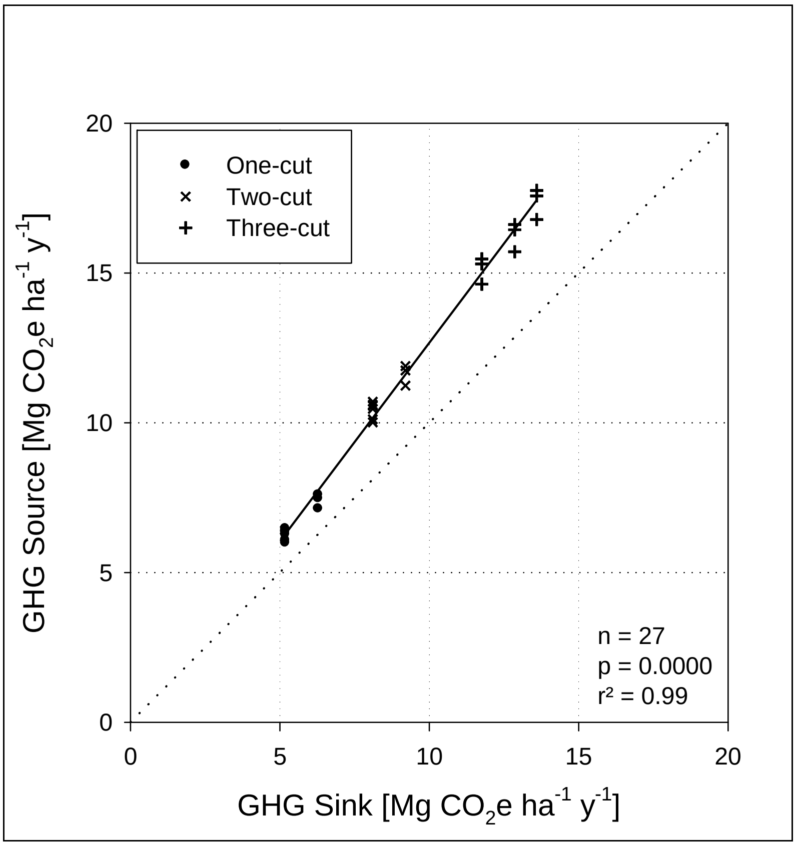

Figure 19: Biofuel GHG sinks plotted against biofuel GHG sources for the factor management intensity. One-cut subsystems are marked by dots, two-cut subsystems by Xs and three cut subsystems by crosshairs. A clear distinction in size of GHG sinks and sources between the three levels of management intensity is visible. One-cut subsystems are closer to the reference line for GHG neutrality which is drawn as dotted line. A regression model shows biofuel GHG sources as function of GHG sinks (BGHGB_source = -0.60 + 1.33 x BGHGB_sink).

Among GHG sources, emissions from biofuel burning (CO_2e_biofuel emissions) were found to be the biggest flux of greenhouse gases (Table 2). All other fluxes were an order of magnitude smaller. N_2O emissions from mineral fertilizer input (CO_2e_N_2O) and emissions from biomass harvest and baling losses (CO_2e_loss harvest; CO_2e_loss baling) were comparable in size. Emissions due to production and provision of fertilizer (CO_2e_fertilizer), emissions from the production of farm machinery (CO_2e_machinery) and emissions from energy input for biofuel conversion (CO_2e _energy input) were smaller. If emissions of fertilizer provision (CO_2e_fertilizer) and on site N_2O emissions (CO_2e_N_2O) were summed up, fertilizer input constituted the second largest flux of greenhouse gases with on average 13 % of the total GHG source.

Table 2: Relative size of greenhouse fluxes compared to the total GHG source.

Flux	% of GHG source (mean)	SD
CO_2e_biofuel emissions	63.8	± 2.2
CO_2e_N_2O	8.2	± 2.4
CO_2_loss harvest	7.8	± 0.3
CO_2_loss baling	7.0	± 0.3
CO_2e_fertilizer	5.0	± 1.5
CO_2e_machinery	3.4	± 1.2
CO_2e_energy input	2.1	± 1.6
CO_2e_management	1.1	± 0.2
CO_2e_farm	1.0	± 0.4

Note: Percentages of fluxes were calculated as fraction to the cumulative GHG source.

The biofuel GHG sink was found to be constituted to the greatest part by net CO_2 exchange in grasslands (F_CO_2) with on average 99.4 % of the total GHG sink. Oxidation of atmospheric methane constituted on average 0.6% of the total GHG sink.

A one-way ANOVA showed a significant (95 %) difference within means of biofuel GHG balance for the factor management intensity ($p = 0.0000$), but not for the factors elevation ($p = 0.9155$) and conversion processes ($p = 0.4171$). Values for fermentation subsystems exhibited the on average lowest biofuel GHG balances. Means of BGHGB for combustion and gasification subsystems were 30 and 25 % higher than fermentation subsystems.

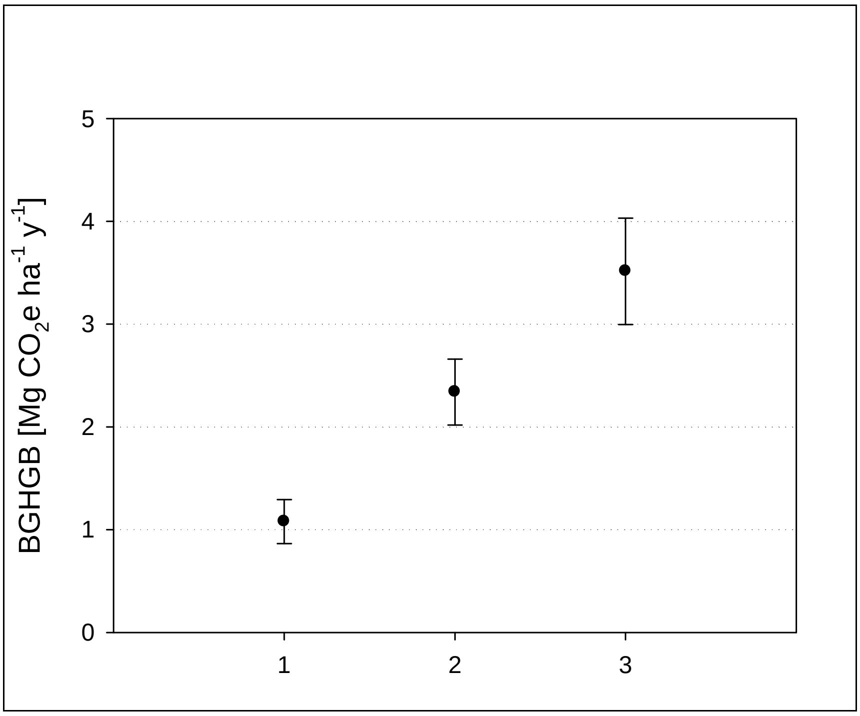

Figure 20: Biofuel GHG balance for the factor management intensity. Numbers code management intensity. The GHG source was found to be different (99%) for the three levels of management intensity. GHG emissions were found to be rising with increasing management intensity. Whiskers show 99 % confidence intervals.

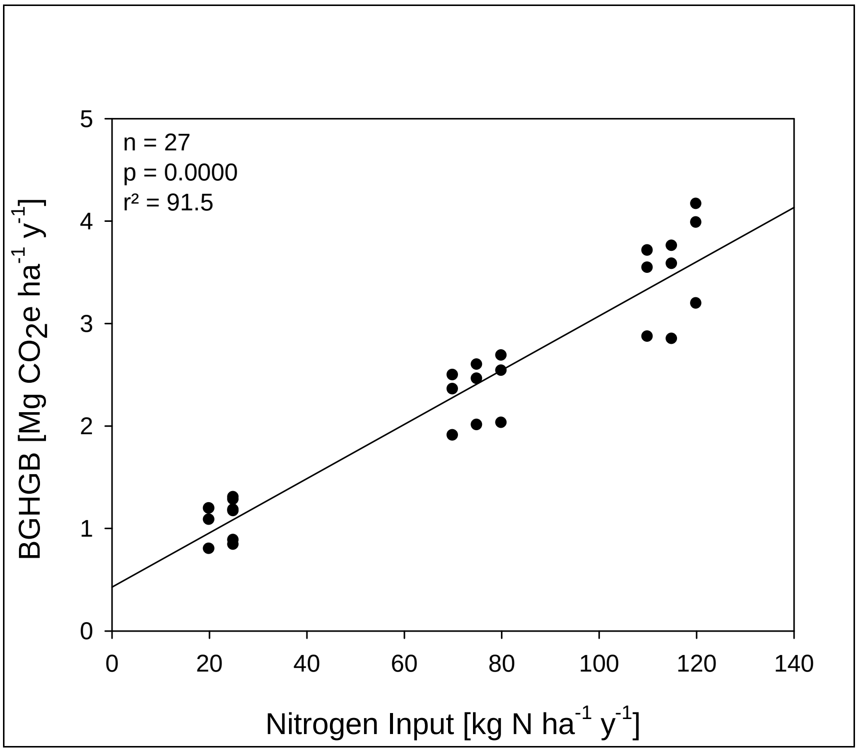

Figure 21: Linear regression model for fertilizer input and biofuel GHG balance (BGHGB). There is a significant (99 %) relationship between nitrogen fertilizer input and biofuel greenhouse gas emissions (p = 0.0000). The regression model indicated a relatively strong relationship between the two variables (sigma = 0.957).

3.2.2. Biofuel GHG ratio (BGHGR)

The 'biofuel greenhouse gas ratio' was calculated as ratio of biofuel GHG sink to source. A BGHGR in excess of one would indicate a subsystem which is a net sink for greenhouse gases.

All subsystems were found to be net greenhouse gas sources, reflected in a mean value for BGHGR of 0.8 (± 0.03), indicating that on average 20 percent of GHG emissions could not be fixed during the biofuel life cycles. Across all subsystems about 12 to 24 % of the total biofuel GHG source could not be fixed. Regarding greenhouse gases, fermentation scenarios (17 % more GHG emitted) and one-cut subsystems (16 % more GHG emitted) exhibited least GHG emissions. From a GHG cycling perspective, an extensive scenario with fermentation for biofuel conversion shows the best results. The minimal BGHGR of 0.76 was found for the subsystem mountain/two-cut/combustion. The maximal BGHGR of 0.88 marked the subsystem valley/one-cut/fermentation, demonstrating that almost 90 of total GHG emissions could be fixed within this biofuel life cycle.

A one way ANOVA showed significant (95 %) differences within means of BGHGR for the factors management intensity (p = 0.0000) and conversion process (p = 0.038), but not for the factor elevation (p = 0.6002).

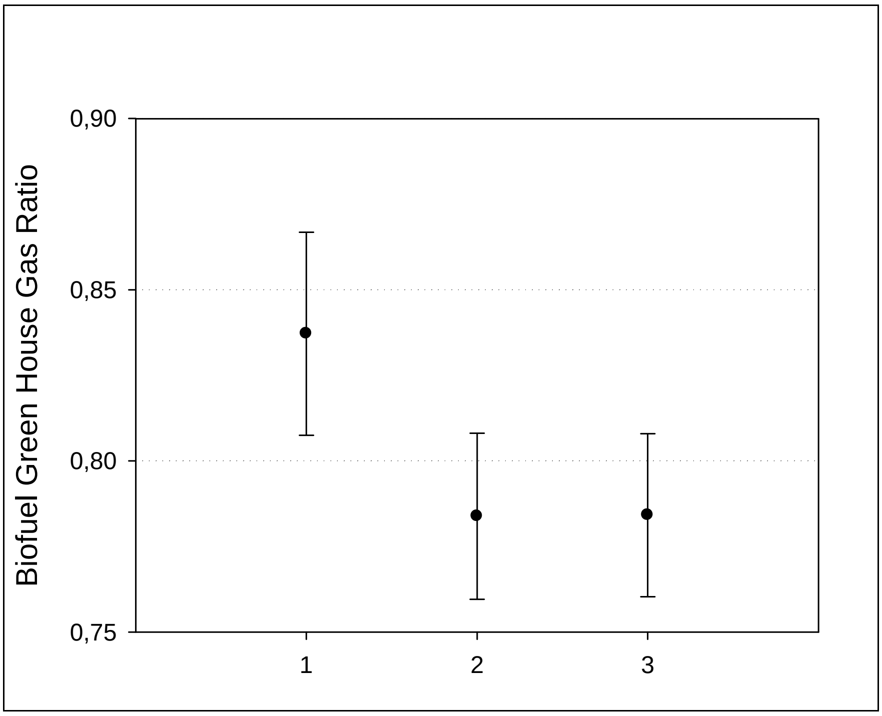

Figure 22: Biofuel GHG ratios for the factor management intensity. Numbers code management intensity. One-cut subsystems exhibited larger values for BGHGR than two or three-cut subsystems. Whiskers show 99 % confidence intervals.

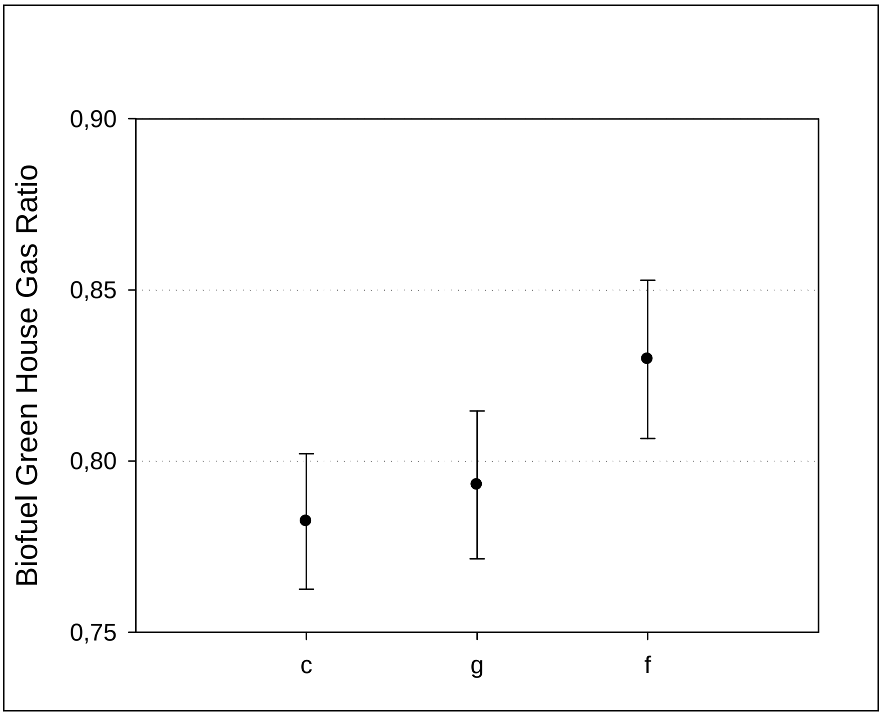

Figure 23: Biofuel GHG ratios for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Means of fermentation subsystems were found to be higher than means of gasification and combustion subsystems. Whiskers show 99 % confidence intervals.

3.2.3. Avoided emissions - Net GHG balance (NGHGB)

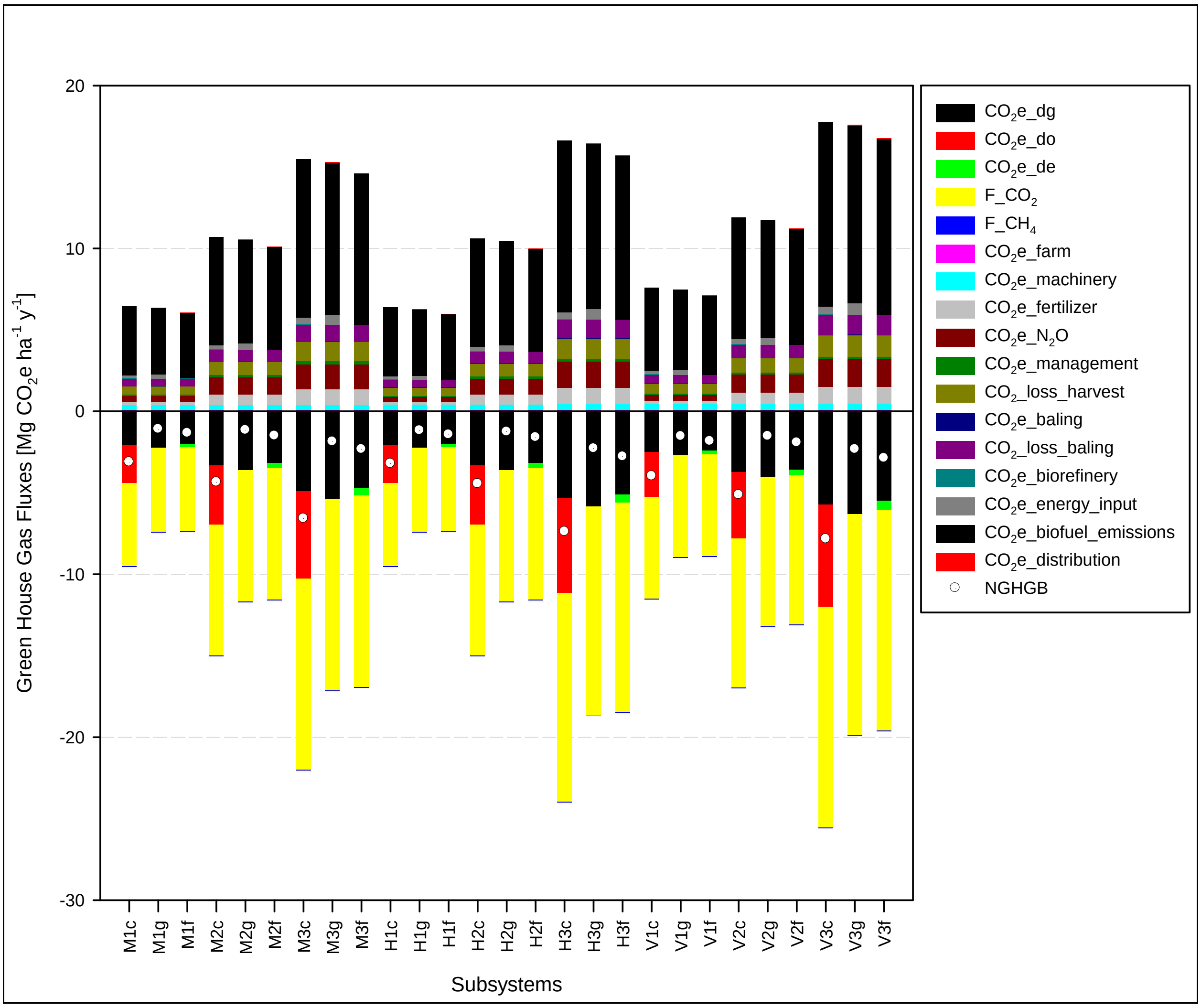

Figure 24: Net GHG balance with constituent GHG fluxes. Dots mark values of NGHGB, calculated as sum of BGHGB and avoided emissions. Subsystems are coded according to mean elevation above sea level (M = mountain, H = hillside, V = valley), management intensity (1 = one-cut, 2 = two-cut, 3 = three-cut) and conversion processes (c = combustion (CHP), g = gasification (bio-SNG), f = fermentation (LC-etOH).

All subsystems were found to successfully avoid GHG emissions compared to the reference scenario (‘Avoided Emissions – Net Greenhouse Gas Balance’). This was reflected in a mean for NGHGB of minus 2.88 Mg CO_2e ha^{-1} y^{-1} (median: - 2.27). The maximum GHG saving potential of 7.83 Mg CO_2e ha^{-1} y^{-1} was found for the subsystem valley/three-cut/combustion, contrasted by the minimal GHG saving potential of 1.09 Mg CO_2e ha^{-1} y^{-1} for the subsystem mountain/one-cut, gasification.

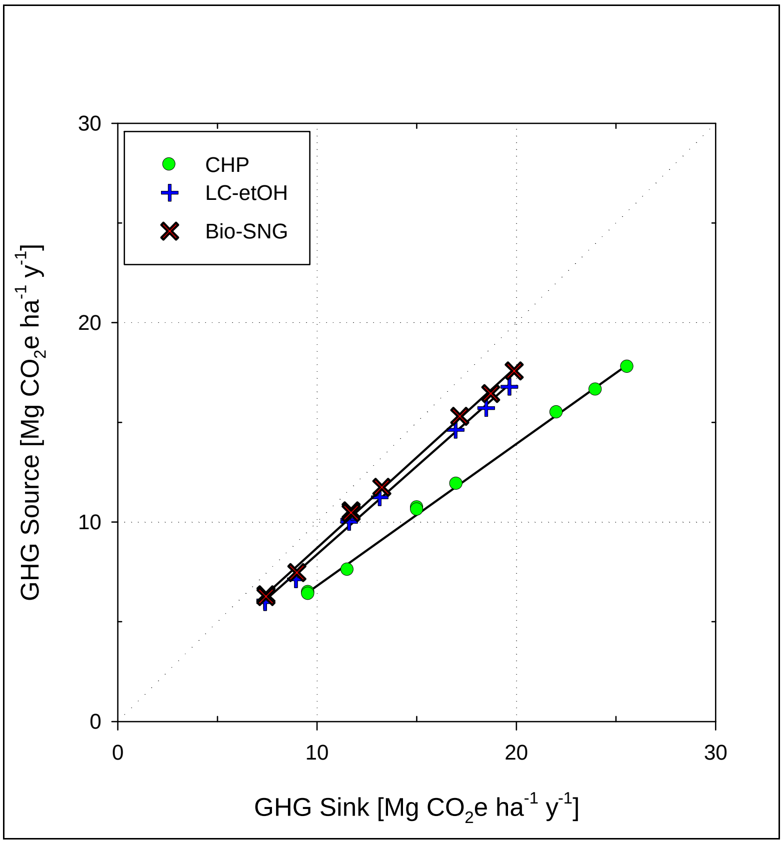

Figure 25: Net GHG sinks and sources according to biofuel conversion processes. Net GHG sinks are plotted against net GHG sources. Combustion subsystems are marked by dots, fermentation subsystems are depicted by crosshairs and gasification subsystems are identified by Xs. Regression models show GHG sources as function of GHG sinks for the different biofuel conversion processes (combustion (CHP): NGHG_source = -0.33 + 0.71 * NGHG_sink; fermentation (LC-etOH): NGHG_source = -0.45 + 0.88 * NGHG_sink; gasification(bio-SNG): NGHG_source = -0.38 + 0.91 * NGHG_sink).

Among net GHG sinks, different averages were found according to conversion process. For gasification and fermentation subsystems grassland gas exchange (F_CO_2) showed the biggest flux followed by the emission bonus for avoided emissions of gasoline (CO_2e_dg). In combustion scenarios, displacement of light oil for heating (CO_2e_do) amounted to more CO_2e than the displaced fossil fuel (Table 3).

A one-way ANOVA showed a significant (95 %) difference within means of NGHGB for the factor conversion process (p = 0.0000) but not for the factors management intensity (p = 0.0761) and elevation (p = 0.9406).

Table 3: Relative size of GHG fluxes for different conversion processes.

Conversion process	CHP		Bio-SNG		LC-etOH	
Flux	% GHG sink	SD	% GHG sink	SD	% GHG sink	SD
F_CO_2	53.5	± 0.3	68.8	± 0.4	69.4	± 0.2
CO_2e_dg	22.0	± 0.2	30.8	± 0.6	27.3	± 0.3
CO_2e_do	24.1	± 0.2	-	-	-	-
CO_2e_de	-	-	-	-	2.8	± 0.0
CO_2e_CH_4	0.3	± 0.2	0.4	± 0.2	0.4	± 0.2

Note: Percentages are means for each conversion process calculated as fraction of the respective flux compared to the total GHG sink.

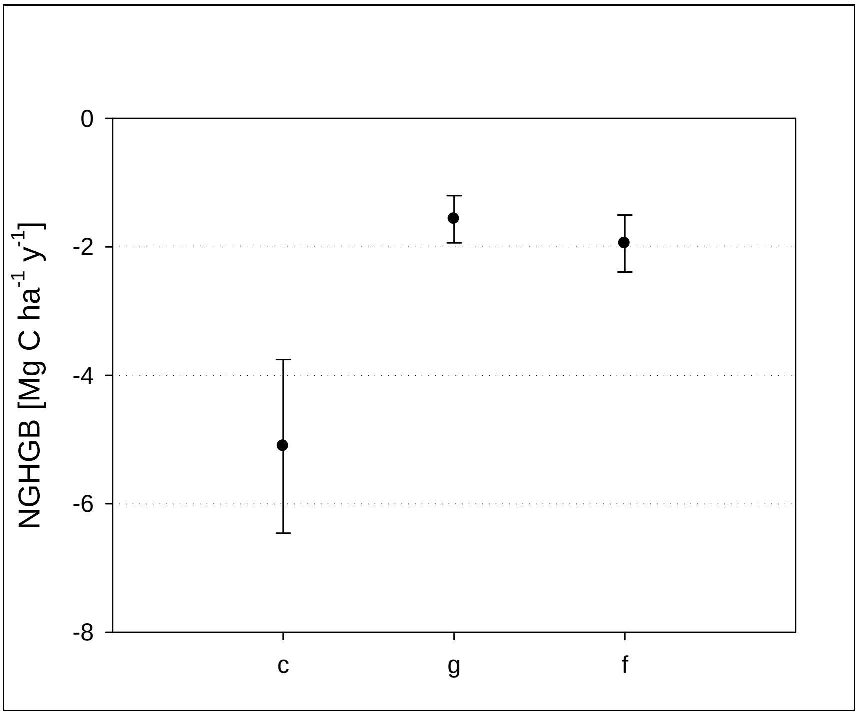

Figure 26: Net GHG balances the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). GHG sinks of combustion subsystems were found to be significantly (99 %) bigger than sinks of fermentation and gasification subsystems. Whiskers show 99 % confidence intervals.

3.2.4. Net GHG ratio (NGHGR)

The 'net greenhouse gas ratio' was calculated as ratio between net GHG sink to source. A value for NGHGR in excess of one implies GHG savings compared to the reference situation ('Net greenhouse gas balance').

All subsystems were found to avoid GHG emissions compared to the reference scenario with a mean value for NGHGB of 1.26 (± 0.14), indicating that subsystems save on average 26% more CO_2-equivalents than were emitted during the biofuel life cycle. The maximum value for NGHGR of 1.5 indicated that the subsystem valley/one-cut/combustion was able to save 50% more greenhouse gases than have been emitted during the biofuel life cycle. The minimum value of 1.1 indicated that 10 % more GHG could be saved than have been emitted during the life cycle of subsystem mountain/two-cut/gasification.

A one-way ANOVA showed a significant (95 %) difference within means of NGHGR for the factor conversion process (p = 0.0000) but not for the factors management intensity (p = 0.4954) and elevation (p = 0.9406).

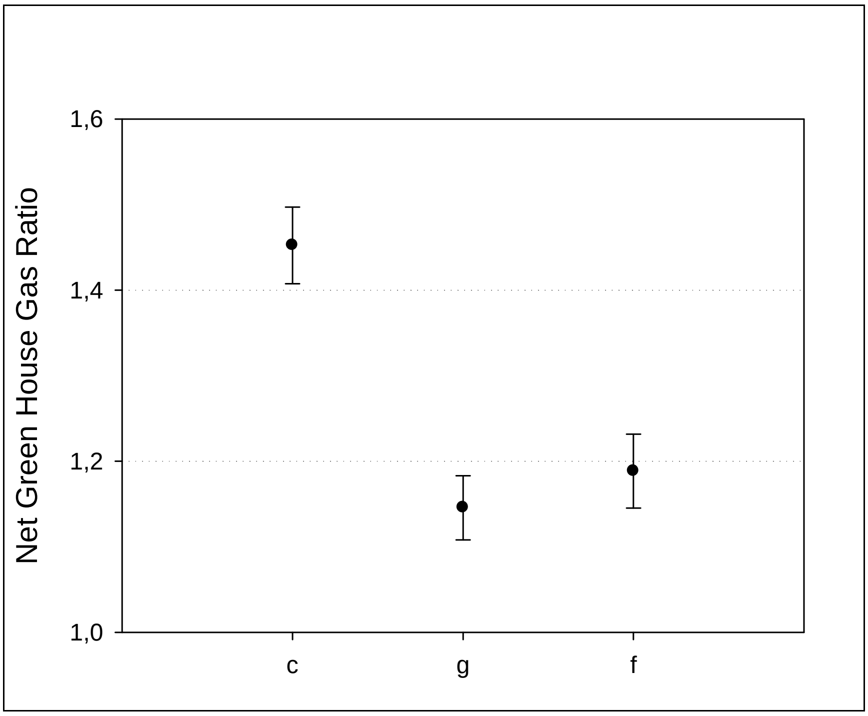

Figure 27: Net GHG ratios for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG) and, f = fermentation (LC-etOH)). Means of NGHGR were found to be significantly (99 %) higher for combustion subsystems compared to fermentation or gasification subsystems. Whiskers show 99 % confidence intervals.

3.3. Energy fluxes

3.3.1. Net energy balance (NEB)

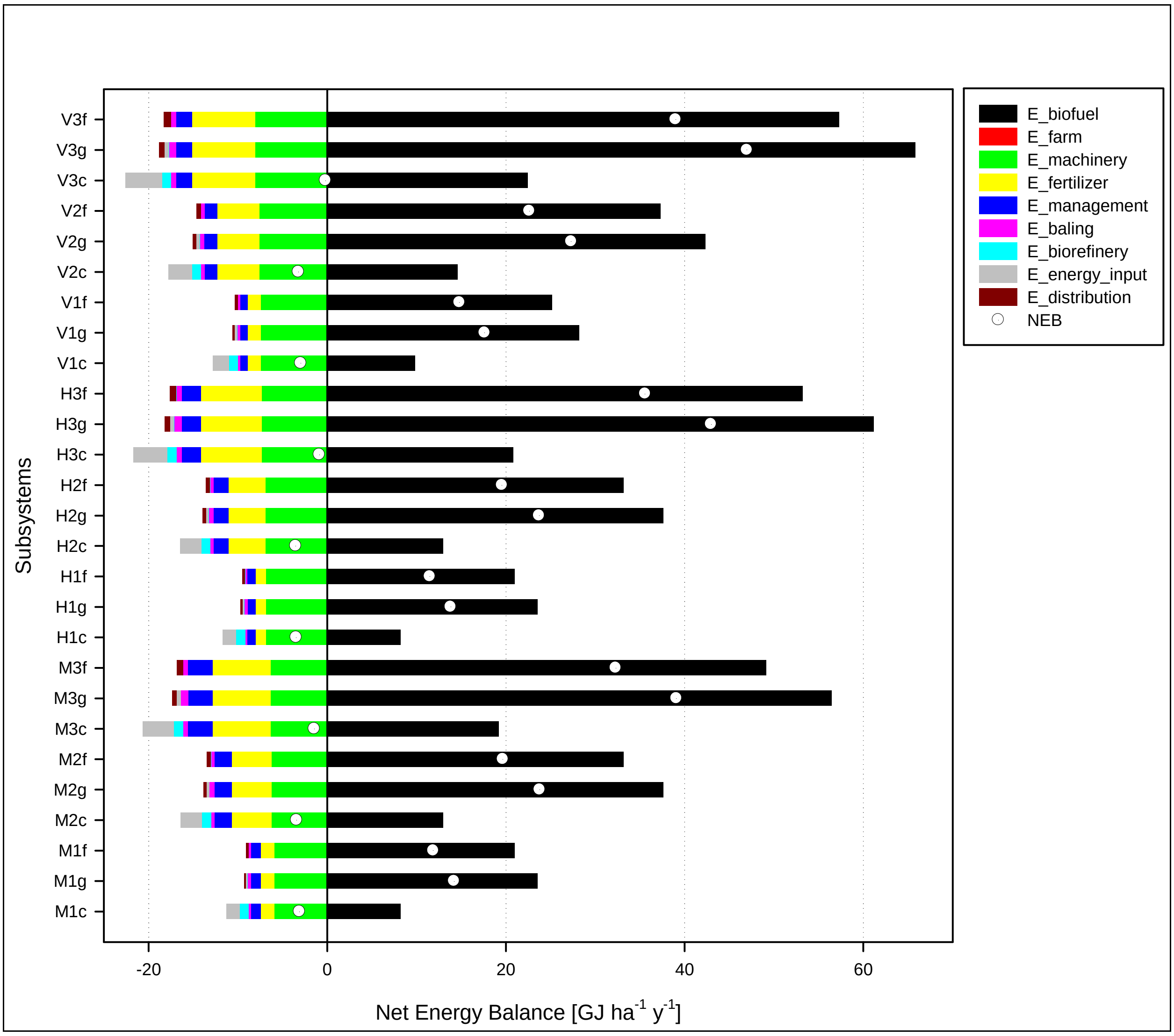

Figure 28: Net energy balance with constituent energy fluxes. Dots show values of NEB, calculated as sum of energy inputs and energy content of the biofuel. Subsystems are coded according to mean elevation above sea level (M = mountain, H = hillside, V = valley), management intensity (1 = one-cut, 2 = two-cut, 3 = three-cut) and conversion processes (c = combustion (CHP), g = gasification (bio-SNG), f = fermentation (LC-etOH).

The energy content of the biofuels produced was not always found to exceed the sum of energy inputs. Although all subsystems NEB exhibited an on average positive NEB with a mean value of 16.1 GJ ha^{-1} y^{-1} (median 14.8), combustion subsystems showed negative net energy balances. The minimum NEB was found for the subsystem hillside/two-cut/combustion with minus 3.5 GJ ha^{-1} y^{-1}. The maximum NEB implied an energy gain of 47 GJ ha^{-1} y^{-1} for the subsystem valley/three-cut/gasification.

Energy inputs (Table 4) were found to consist largely of cumulative energy demand for the production of agricultural machinery (E_machinery). The second-biggest energy flux, cumulative energy demand for fertilizer provision (E_fertilizer), was about half as big. Energy invested in grassland management (E_management) accounted for about ten percent of energy inputs. Energy inputs for biofuel conversion (E_energy input), baling and transport (E_baling), cumulative energy demand for biorefineries (E_biorefinery) and biofuel distribution (E_distribution) ranged between two and six percent of total energy input. The energy invested for the provision of farm buildings (E_farm) was marginal with on average 0.1 % of total energy input.

Table 4: Relative size of energy input fluxes compared to the total energy input.

Flux	% of Energy Input	SD
E_machinery	49.7	± 12.5
E_fertilizer	26.2	± 10.0
E_management	10.9	± 2.6
E_energy input	5.8	± 6.9
E_baling	3.0	± 0.7
E_biorefinery	2.3	± 3.1
E_distribution	2.1	± 1.6
E_farm	0.1	± 0.0

Note: Values are means across all subsystems, calculated as fraction of energy flux to total energy input.

A one-way ANOVA showed a significant (95 %) difference within means of NEB for the factor conversion process ($p = 0.0000$), but not for the factors management intensity ($p = 0.0559$) and elevation ($p = 0.9124$).

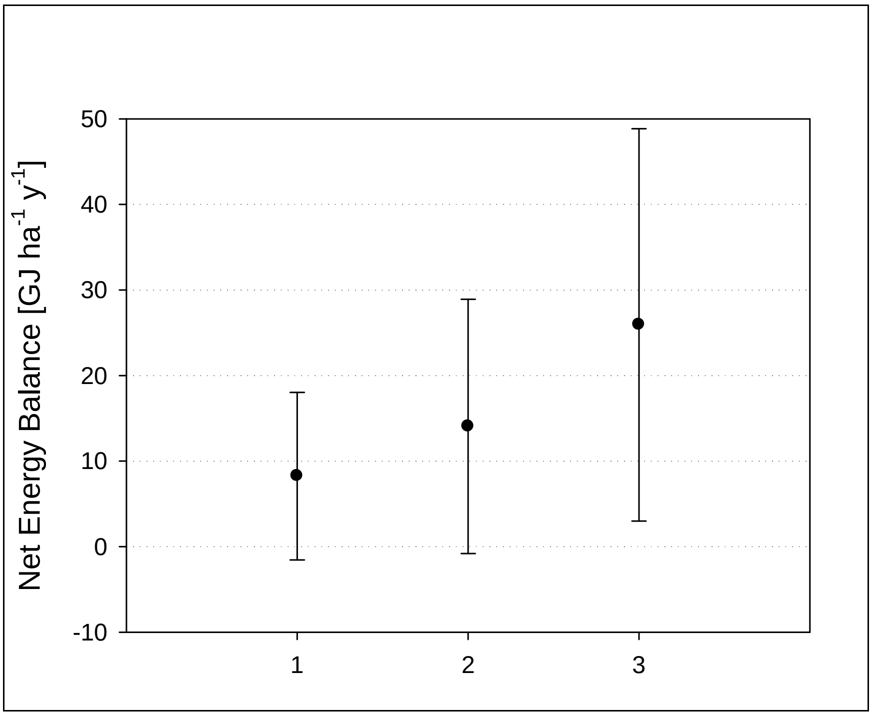

Figure 29: Net energy balances for the factor management intensity. Numbers code management intensity. No significant (95 %) variance was found within NEB values for the factor management intensity (p = 0.0559). Whiskers show 99 % confidence intervals.

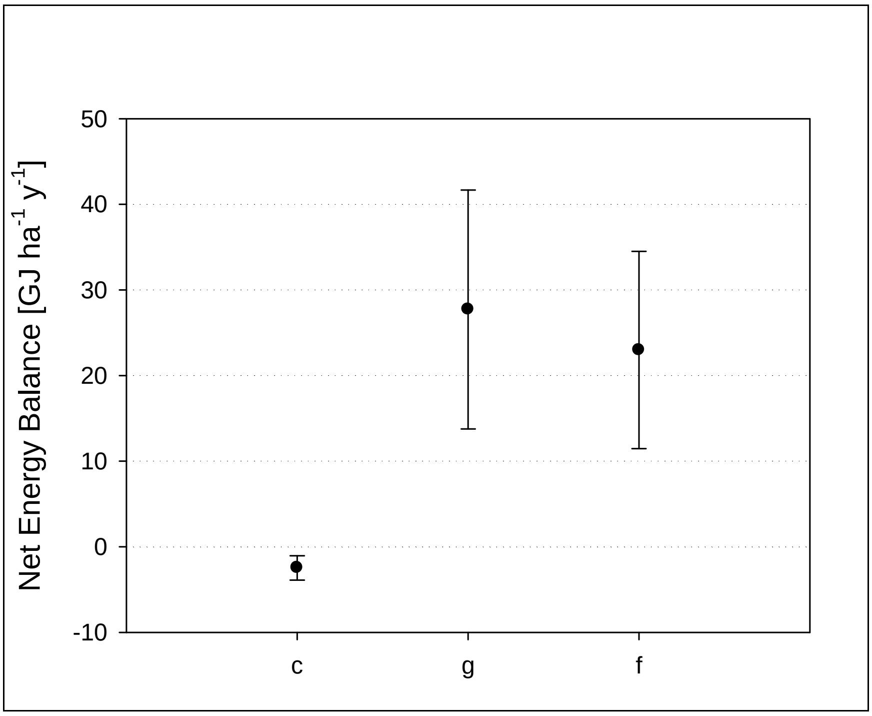

Figure 30: Net energy balances for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), g = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Means of NEB were significantly (99 %) lower for combustion subsystems than for gasification or fermentation subsystems. Gasification subsystems returned the highest values for NEB. Whiskers show 99 % confidence intervals.

3.3.2. Net energy ratio (NER)

The ‘net energy ratio’ was calculated as ratio of biofuel energy to total energy input. An NER exceeding one indicates a net energy gain for the investigated biofuel life cycle and can therefore be stated as renewable.

The studied subsystem exhibited a mean value for NER of 2.11 (± 0.97), implying that the subsystems yielded on average 200 % of total energy input. The minimum NER of 0.70 indicated an energy loss of around 30 % for the subsystem hillside/one-cut/combustion, contrasted by a maximum value for NER of 3.49, which implied an energy gain of 250 % for the subsystem valley/three-cut/gasification.

A one-way ANOVA showed a significant (95 %) difference within means of NER for the factor conversion process (p = 0.0000) (Figure 30), but not for the factors management intensity (p = 0.4222) and elevation (p = 0.9602).

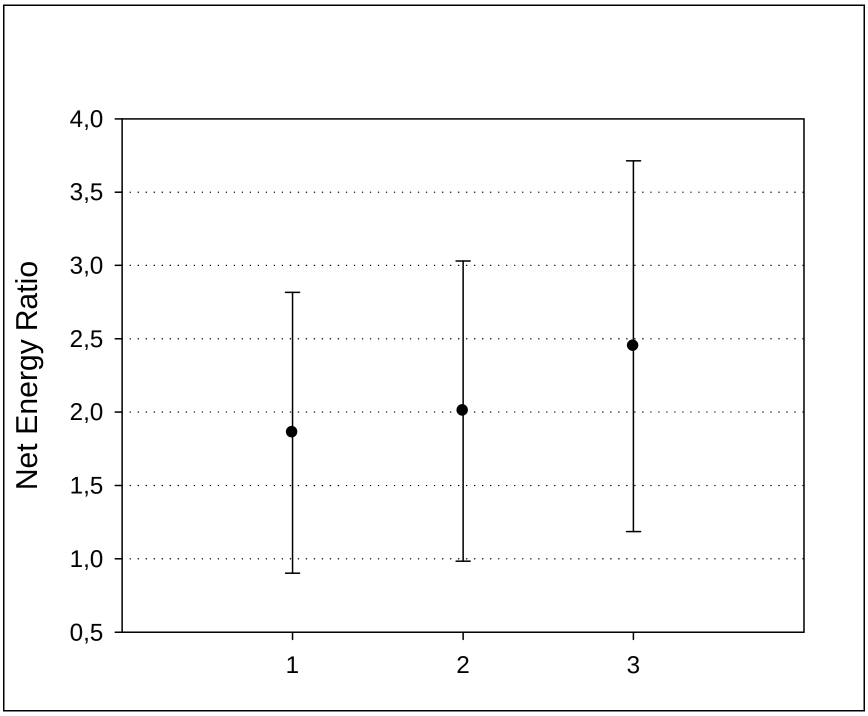

Figure 31: Net energy ratios for the factor management intensity. Numbers code management intensity. No significant (95 %) difference was found within NER values for the factor management intensity. Whiskers show 99 % confidence intervals.

3.3.3. Net Energy balance including co-products (NEB_CP)

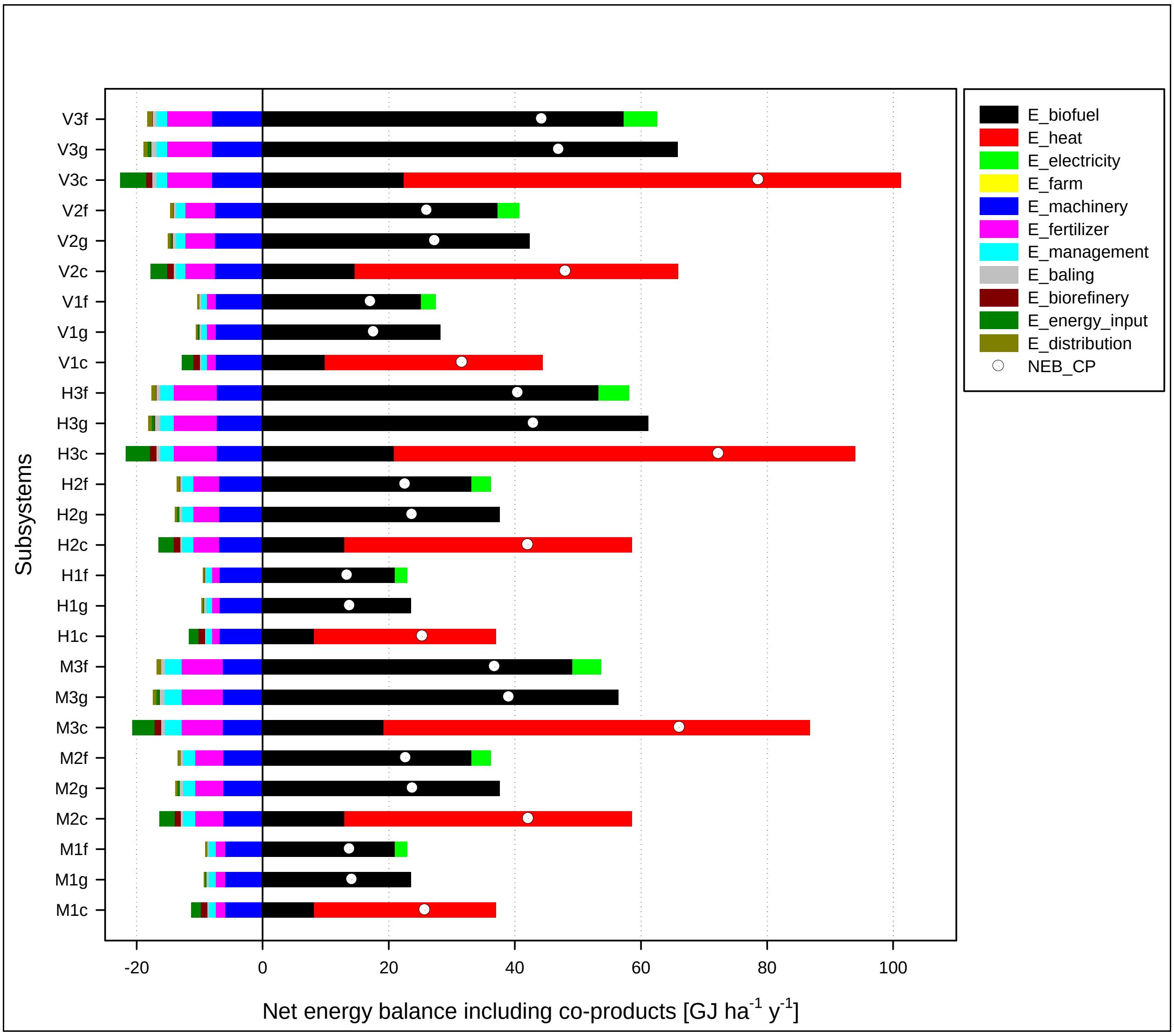

Figure 32: Net energy balance including co-products (NEB_CP) with constituent energy fluxes. Dots mark values for NEB_CP, calculated as sum of input energy, biofuel energy and co-product energy. Subsystems are coded according to mean elevation above sea level (M = mountain, H = hillside, V = valley), management intensity (1 = one-cut, 2 = two-cut, 3 = three-cut) and conversion processes (c = combustion (CHP), g = gasification (bio-SNG), f = fermentation (LC-etOH).

The net energy balance including co-products was positive for all subsystems, with an average NEB_CP of 34 GJ ha^{-1} y^{-1} (median 27.3), indicating an energy gain for all subsystems. The minimum NEB_CP was found for the subsystem hillside/one-cut/fermentation with 13.4 GJ ha^{-1} y^{-1}, contrasted by a maximum value for NEB_CP of 78.6 GJ ha^{-1} y^{-1} in the subsystem valley/three-cut/combustion.

Energy outputs of the NEB_CP were constituted differently according to conversion pathway. In gasification subsystems, biofuel energy accounted for 100 % of biofuel energy. In combustion subsystems, electric energy used for transport - here referred to as biofuel energy - represented 22.1 %, and heat energy 77.9 % of total energy output. Fermentation scenarios exhibited an energy output constituted to 91.5 % of biofuel energy and 8.5 % of electric energy output.

A one-way ANOVA revealed significant (95 %) differences within means of NEB_CP for the factors management intensity (p = 0.0000) and conversion process (p = 0.0091) but not for the factor elevation (p = 0.7805).

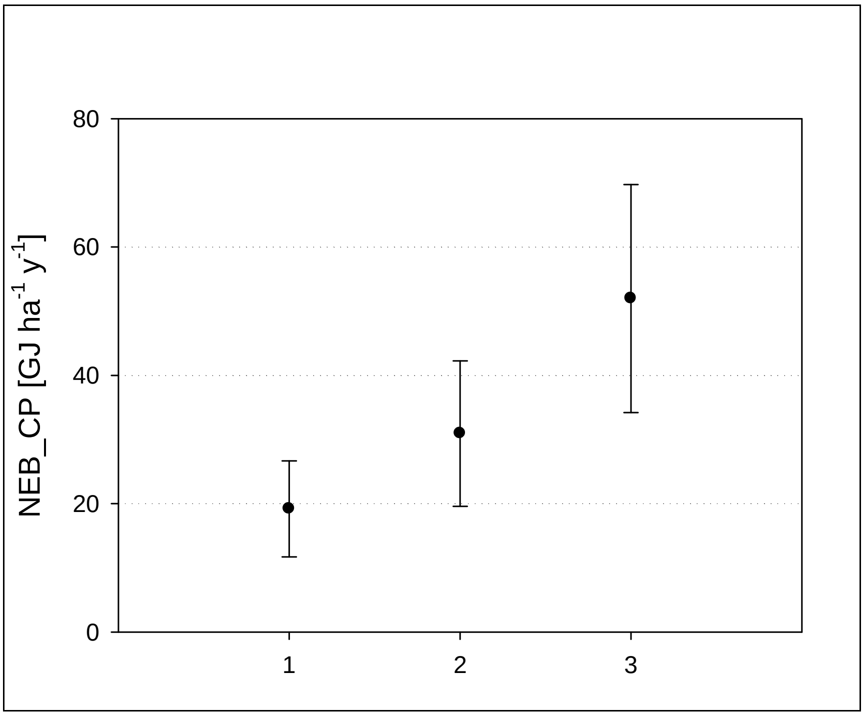

Figure 33: Net energy balances including co-products for the factor management intensity. Numbers code management intensity. One-cut subsystems differed significantly (99%) from three-cut subsystems. Whiskers show 99 % confidence intervals.

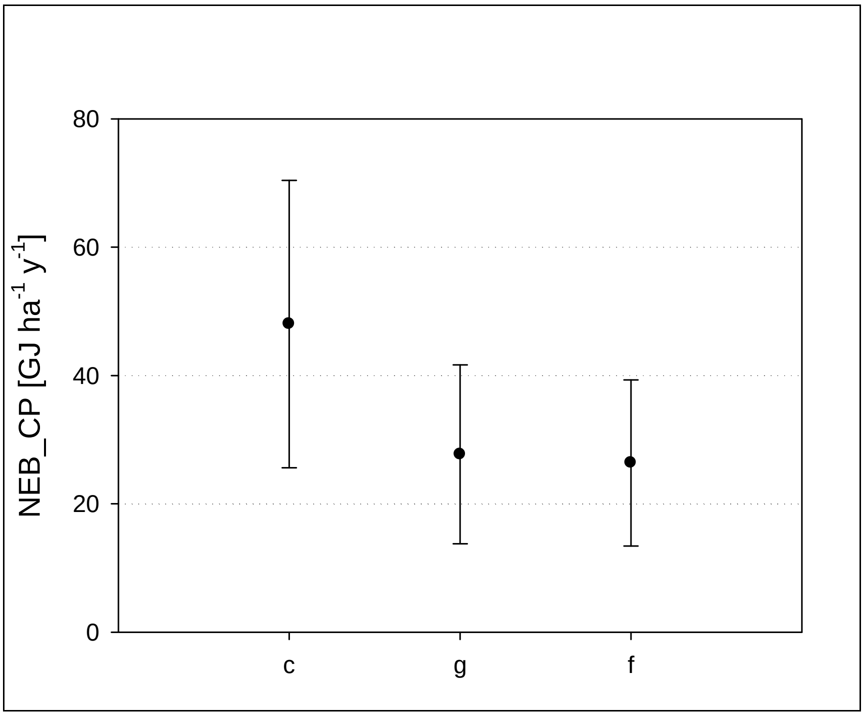

Figure 34: Net energy balances including co-products for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Combustion subsystems returned higher values for NEB_CP than fermentation and gasification scenarios. Whiskers show 99 % confidence intervals.

Table 5: Means of net energy balance incl. co-products for different conversion processes.

Conversion process	NEB_CP [GJ ha^{-1} y^{-1}]
Combined Heat and Power	48.0
Bio-SNG	27.7
LC-etOH	26.4

Note: Means are calculated across all management intensities and levels of elevation for each conversion process

3.3.4. Net energy ratio including co-products (NER_CP)

The ‘net energy ratio including co-products’ was calculated as the fraction of total energy output to total energy input. An NER_CP higher than one indicates a net energy gain for the investigated biofuel life cycle and can therefore be stated as renewable.

For all subsystems an average value of 3.2 (± 0.6) was found for NER_CP, indicating an average energy gain of more than 200 % of total input energy. The minimum NER_CP of 2.4 exhibited the subsystem hillside/one-cut/fermentation, implying an energy gain of 140 % of total energy input. The maximum NER_CP of 4.5 was found for the subsystem valley/three-cut/combustion, indicating an energy gain of about 350 % of total energy input.

A one-way ANOVA showed significant (95 %) differences within means of NER_CP for the factors management intensity ($p = 0.0012$) and conversion process ($p = 0.0001$), but not for the factor elevation ($p = 0.8606$).

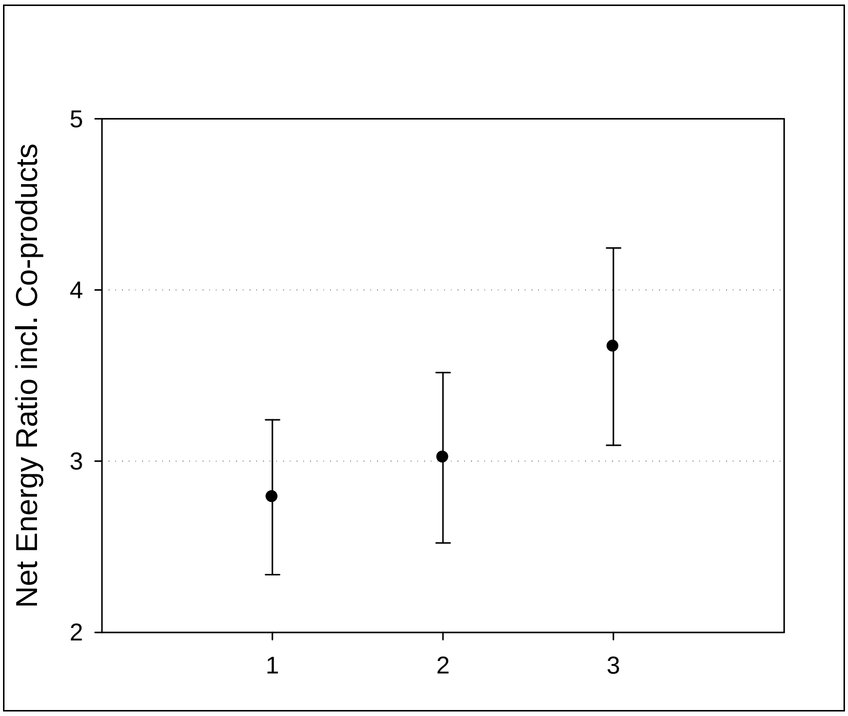

Figure 35: Net energy ratios including co-products for the factor management intensity. Numbers code management intensity. One-cut subsystems exhibited a lower NER_CP than two- and three-cut subsystems. Whiskers show 99 % confidence intervals.

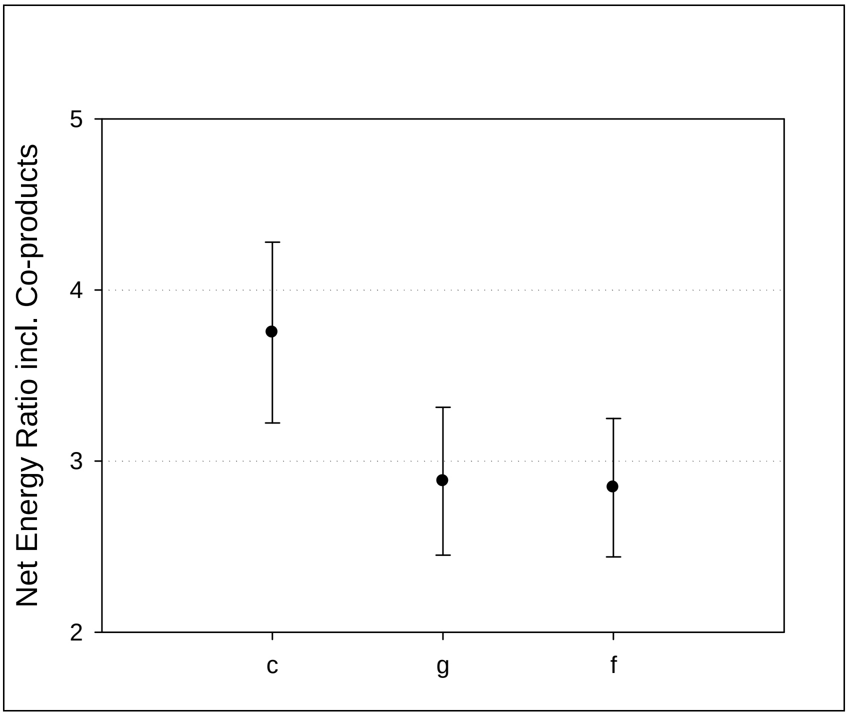

Figure 36: Net energy ratios including co-products for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Combustion subsystems exhibited higher values for NER_CP than fermentation and gasification scenarios (Table 6). Whiskers show 99 % confidence intervals.

Table 6: Net energy ratio including co-products for conversion processes.

Conversion process	NER_CP (mean)	SD
Combustion	3.7	± 0.5
Gasification	2.9	± 0.4
Fermentation	2.8	± 0.4

Note: Means of NER_CP shown here were calculated across all subsystems with the respective conversion process.

3.4. Transport services

3.4.1. Vehicle kilometres per hectare

Total biofuel energy output per unit of land was converted to the number of vehicle kilometres travelled with this amount of energy. Thereby the total output of transport service was calculated per subsystem [vkm ha^{-1} y^{-1}].

Across all subsystems vehicle kilometres per unit of land averaged to 17512 vkm ha^{-1} y^{-1} (median 16774). The smallest transport service of 9430 vkm ha^{-1} y^{-1} was found for the subsystem mountain/one-cut/fermentation, contrasting the subsystem valley/three-cut/gasification with a maximum transport service of 29622 vkm ha^{-1} y^{-1}. On average, gasification subsystems yielded most vehicle kilometres per unit of land (18808 vkm ha^{-1} y^{-1}), followed by combustion scenarios, which yielded eight percent (17217 vkm ha^{-1} y^{-1}), and fermentation scenarios, which yielded twelve percent (16511 vkm ha^{-1} y^{-1}) less vehicle kilometres per unit of land.

A one-way ANOVA showed significant (95 %) differences within vehicle kilometres driven per unit of land for the factor management intensity ($p = 0.000$), but not for the factors conversion process ($p = 0.7551$) and elevation ($p = 0.6830$).

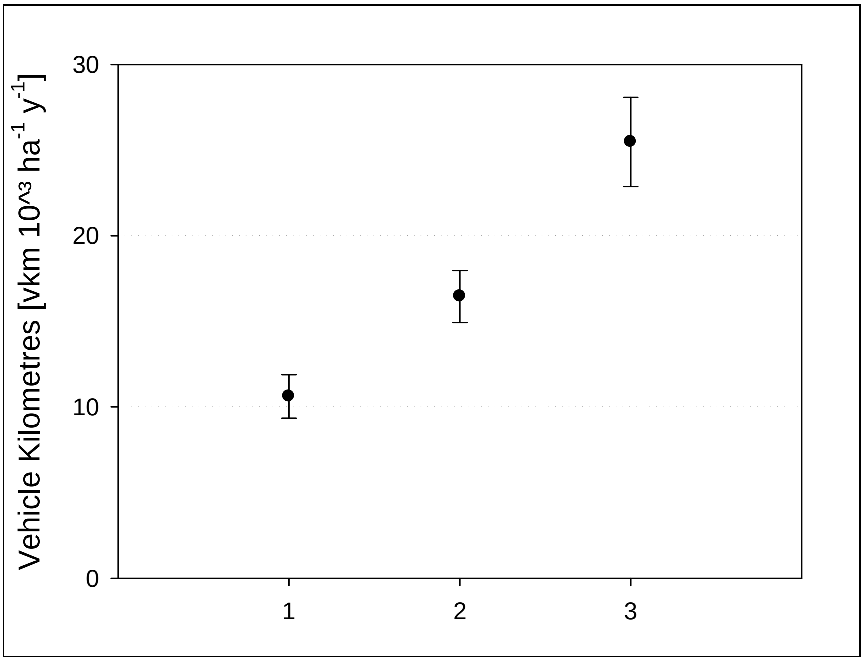

Figure 37: Vehicle kilometres per unit of land for the factor management intensity. Numbers code management intensity. The three levels of management intensity yielded significantly (99%) different amounts of vehicle kilometres per unit of land. Whiskers show 99 % confidence interval.

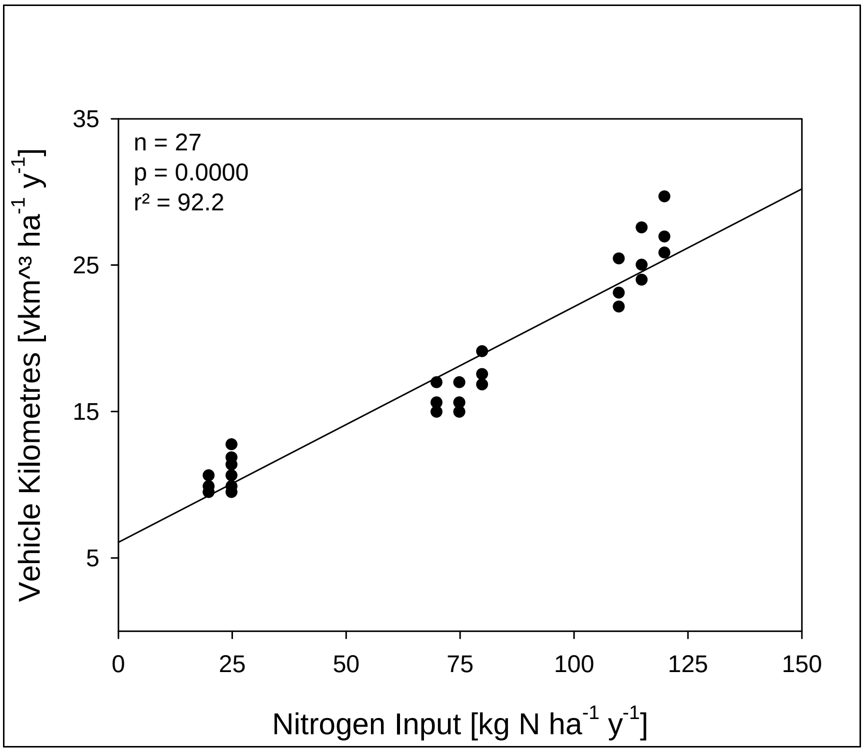

Figure 38: Linear regression model for nitrogen input versus vehicle kilometres per unit of land. There is a highly significant relationship between nitrogen fertilizer input and transport service per unit of land ($p = 0.0000$; $r^2 = 92.9$).

3.4.2. Life cycle carbon emissions of transport services

The amount of biofuel carbon emissions (‘Biofuel carbon balance’) divided by total vehicle kilometres per unit of land was used to reference life cycle carbon emissions of the respective subsystem [mg C vkm^{-1}].

On average, the transport services derived from the subsystems emitted 16 mg C vkm^{-1} (± 4). The least carbon intensive subsystem hillside/three-cut/fermentation emitted 8.3 mg C vkm^{-1}. This contrasted the most carbon intensive transport services provided by the subsystems mountain/one-cut/gasification and mountain/one-cut/combustion which emitted about 22.7 mg C vkm^{-1}.

A one-way ANOVA showed significant (95 %) differences for means of life cycle carbon emissions for the factors management intensity ($p = 0.0089$) and conversion process ($p = 0.0002$), but not for the factor elevation ($p = 0.3020$).

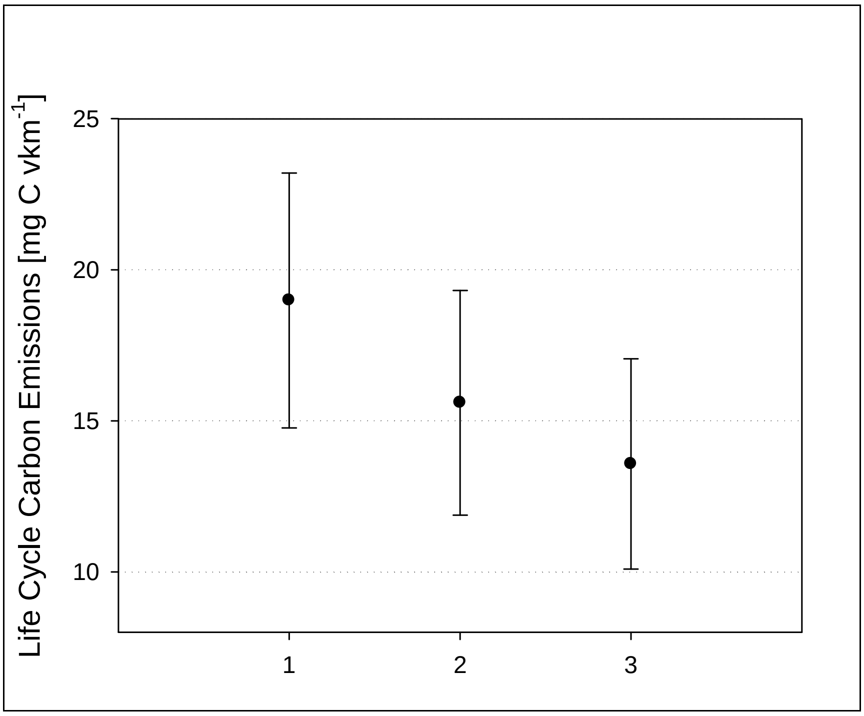

Figure 39: Life cycle carbon emissions of transport services for the factor management intensity. Numbers code management intensity. Means of life cycle carbon emissions for transport services discriminated according to the gradient of management intensity. One-cut subsystems were found to provide a more carbon intensive transport service than three-cut subsystems. Whiskers show 99 % confidence intervals.

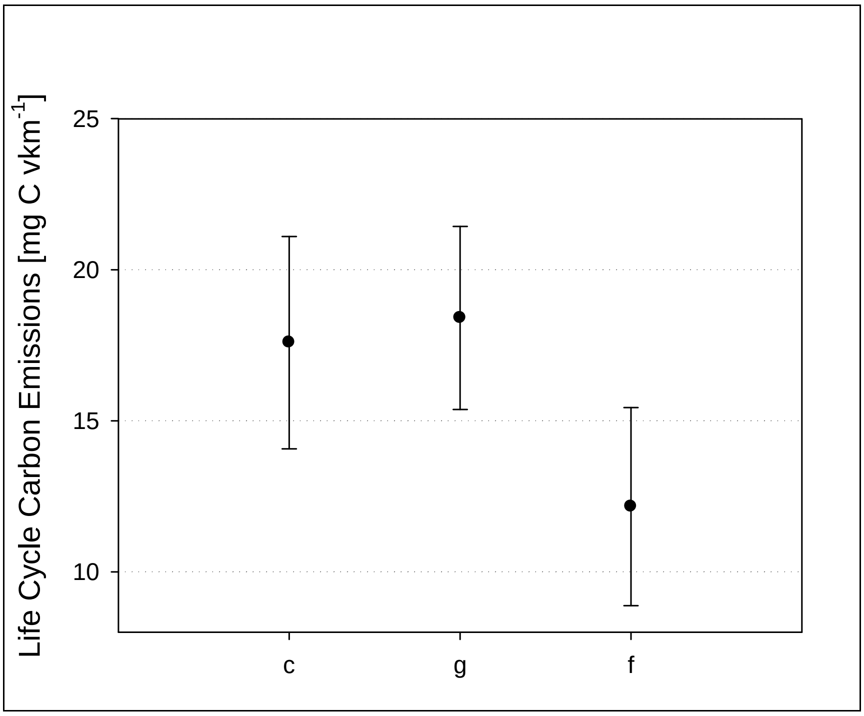

Figure 40: Life cycle carbon emissions of transport services for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Means show a significant (95 %) variance for the factor conversion process (p = 0.0002). Fermentation subsystems emit significantly (99 %) less carbon per vehicle kilometre than gasification subsystems. Combustion subsystems emit slightly less carbon per vehicle kilometre than gasification subsystems. Whiskers show 99 % confidence intervals.

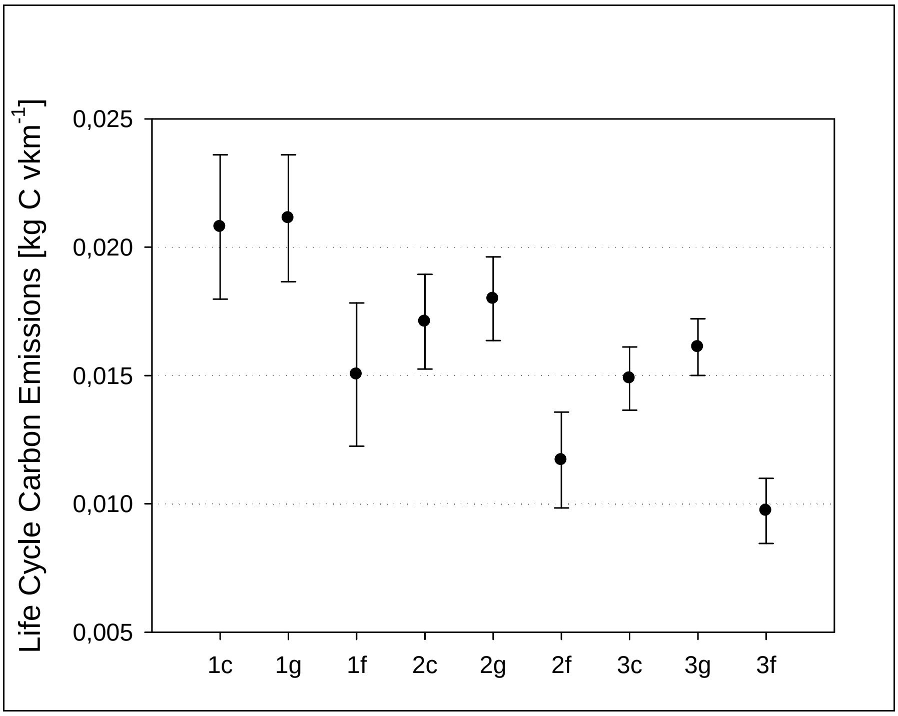

Figure 41: Life cycle carbon emissions for the factors management intensity and conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Numbers code management intensity (cutting frequency). Whiskers show standard deviations.

3.4.3. Life cycle GHG emissions of transport services

The amount of greenhouse gases emitted during the biofuel life cycle ('Biofuel GHG Balance') divided by the number of vehicle kilometres per unit of land was used to reference life cycle GHG emissions of the respective transport service [kg CO_2e vkm^{-1}].

Across all subsystems a mean value of 0.13 kg CO_2e vkm^{-1} (± 0.02) was emitted to drive one kilometre. The minimum value of 0.07 kg CO_2e vkm^{-1} identified the subsystem valley/one-cut/fermentation as least GHG intensive transport service. The most GHG intensive subsystem was mountain/two-cut/combustion 0.17 kg CO_2e vkm^{-1}.

A one-way ANOVA showed significant (95 %) differences within means of life cycle GHG emissions for the factors management intensity (p = 0.0000) and conversion process (p = 0.0067), but not for the factor elevation (p = 0.5453).

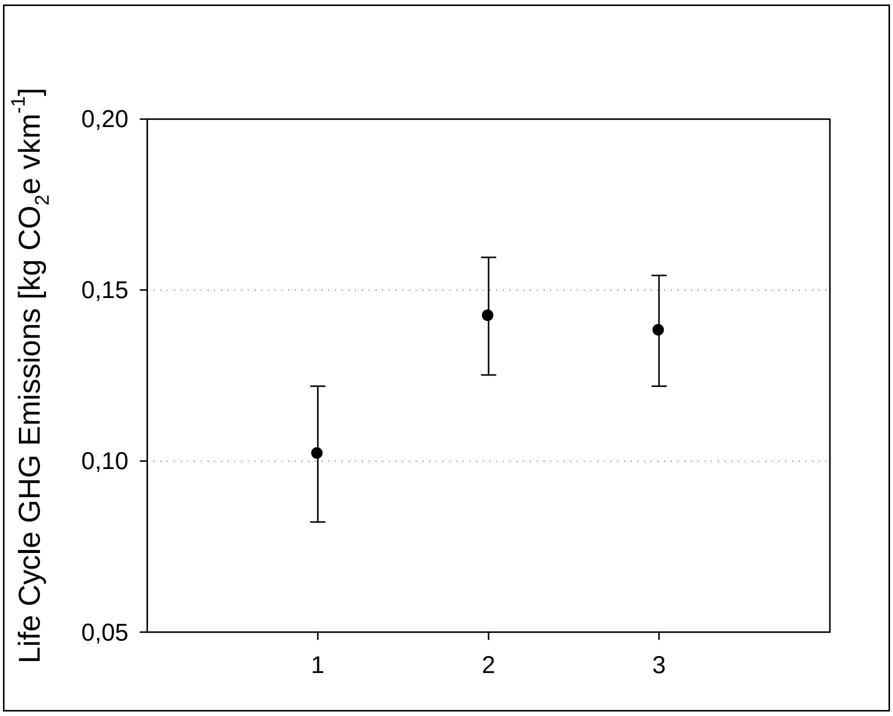

Figure 42: Life cycle GHG emissions of transport services for the factor management intensity. Numbers code management intensity. Subsystems in one-cut management regime were found to emit significantly (99 %) less greenhouse gases compared to two and three-cut subsystems. Whiskers show 99 % confidence intervals.

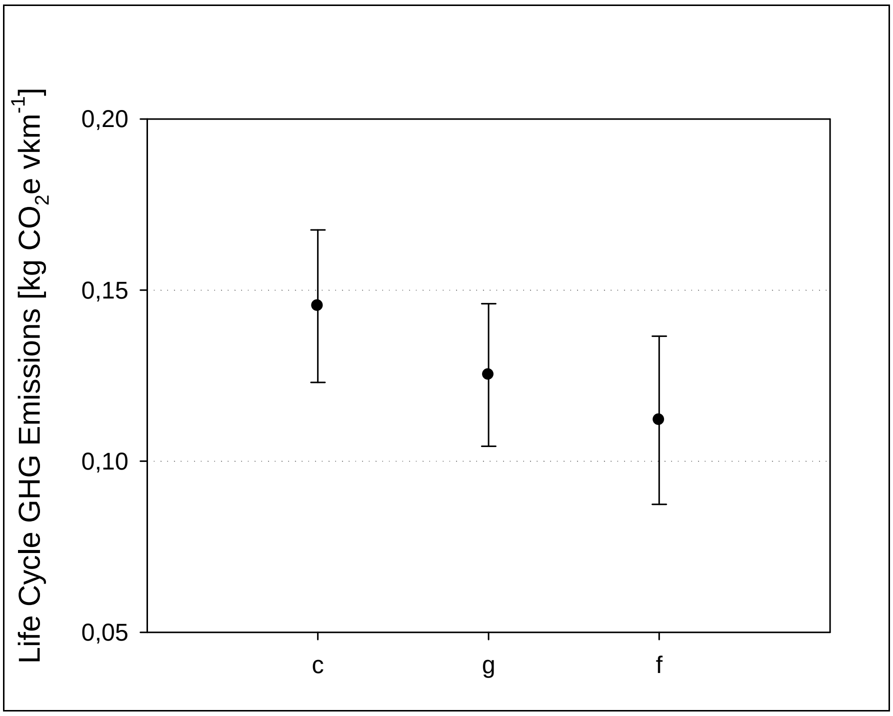

Figure 43: Life cycle GHG emissions of transport services for the factor conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Means of fermentation subsystems were found to be lower than means of combustion subsystems. Whiskers show 99 % confidence intervals.

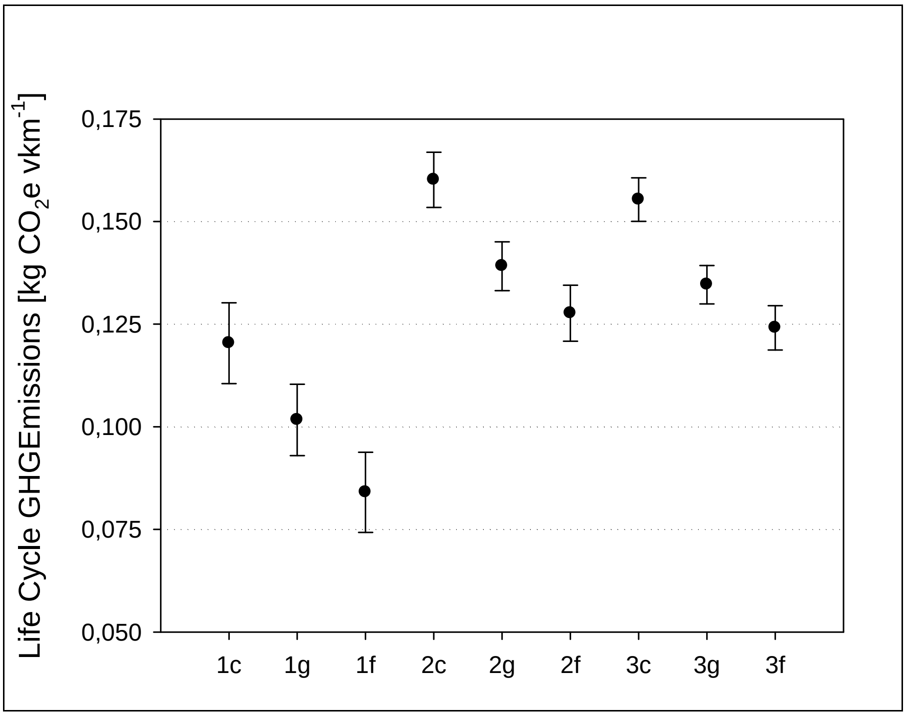

Figure 44: Life cycle GHG emissions of transport services for the factors management intensity and conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Numbers code management intensity (cutting frequency). Whiskers show standard deviations.

3.4.4. Non-renewable energy demand of transport services

The amount of input energy per hectare, as calculated in the net energy balance (‘Net energy balance’), divided by vehicle kilometres travelled per hectare per year was used to calculate the non-renewable energy demand invested for the different transport services [MJ vkm^{-1}].

Across all subsystems, an average of 0.89 MJ (± 0.14) was consumed to drive one kilometre. The least energy intensive transport service was the subsystem valley/three-cut/gasification with 0.64 MJ vkm^{-1}. In contrast, the subsystem hillside/one-cut/combustion was found to be the most energy intensive transport service with a value of 1.19 MJ km^{-1}.

A one-way ANOVA showed significant (95 %) differences within means of non-renewable energy demand of transport services for the factors management intensity ($p = 0.0003$) and conversion process ($p = 0.0005$), but not for the factor elevation ($p = 0.7216$).

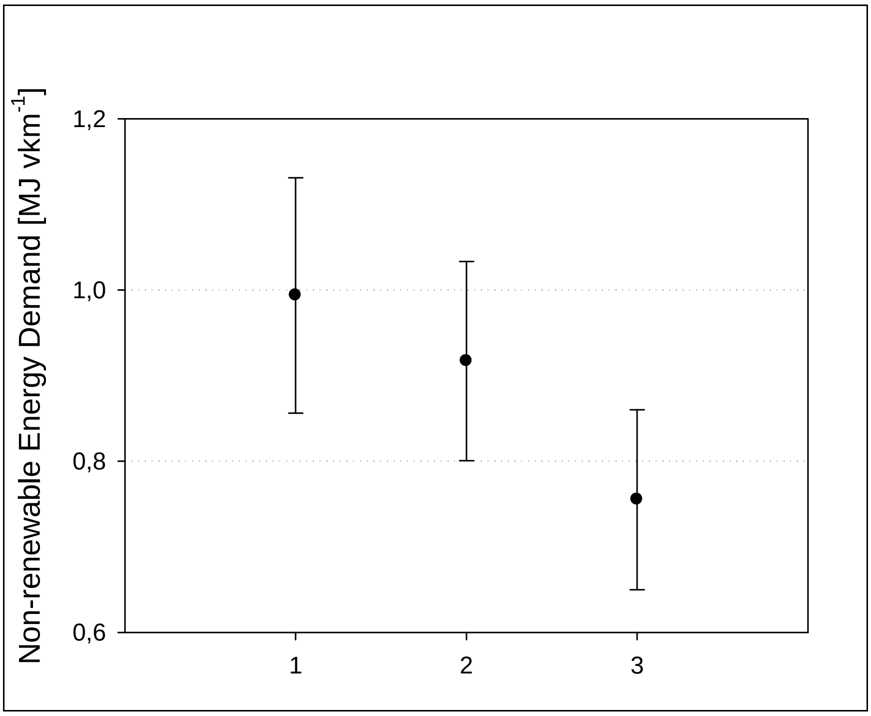

Figure 45: Non-renewable energy demand of transport services for the factor management intensity. Numbers code management intensity. Means of three-cut subsystems were lower than means of one- and two-cut subsystems. One-cut subsystems exhibited the highest non-renewable energy demand. Whiskers show 99 % confidence intervals.

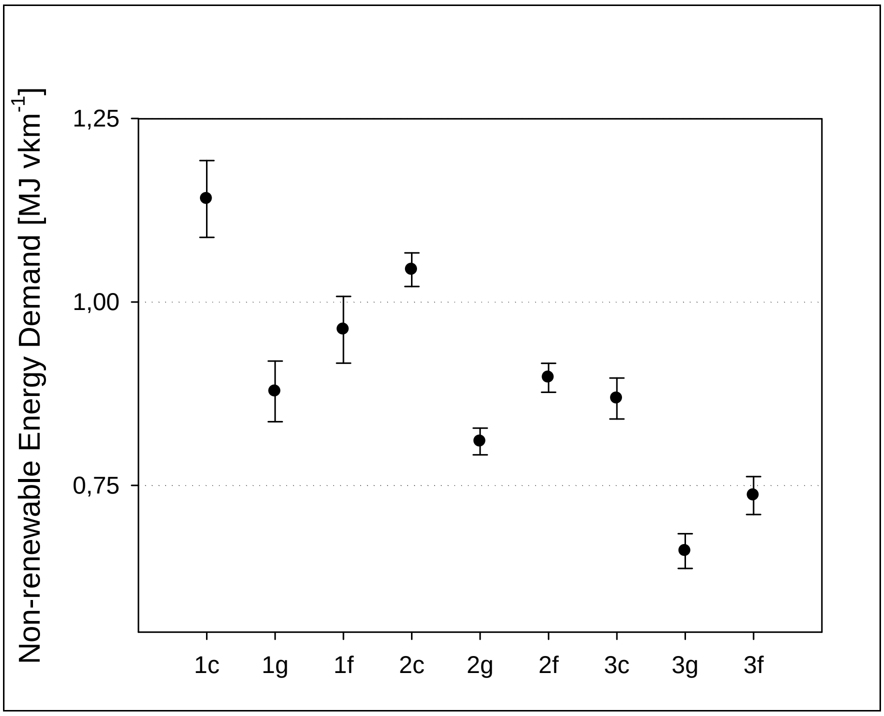

Figure 46: Non-renewable energy demand of transport services for the factors management intensity and conversion process. Letters indicate conversion processes (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)) and numbers code management intensity. Whiskers show standard deviations. A clear distinction was found for the three conversion processes. Combustion subsystems had the highest non-renewable energy demand while gasification subsystems consumed least non-renewable energy.

3.5. Results for management intensities and conversion processes

To show effects of management intensity and conversion process on carbon, GHG and energy balances, the metrics presented above were aggregated for the factors management intensity and conversion process.

Table 7: Energy, carbon and GHG metrics for the factors management intensity and conversion processes.

Differences within each metric (line) were tested in a one-way ANOVA followed by a multiple range test (Tukey HSD). Groups that are not significantly different at the 95% level, are denoted by the same superscript letter.

Subsystems [1]	One-cut			Two-cut			Three-cut		
	c	g	f	c	g	f	c	g	f
Carbon									
ECB [2]	6.72^{a}	9.42^{a}	-0.08^{a}	-16.41^{a}	-12.29^{a}	-26.80^{a}	-6.94^{a}	-0.66^{a}	6.72^{a}
ECR [3]	0.99^{a}	0.99^{a}	1.00^{a}	1.01^{a}	1.00^{a}	1.01^{a}	1.00^{a}	1.00^{a}	1.01^{a}
BCB [4]	0.22^{bc}	0.24^{bc}	0.15^{a}	0.28^{cd}	0.32^{de}	0.18^{ab}	0.37^{e}	0.44^{f}	0.23^{bc}
BCR [5]	0.87^{ab}	0.86^{a}	0.91^{cde}	0.89^{abc}	0.88^{abc}	0.93^{de}	0.90^{bcd}	0.89^{abc}	0.94^{e}
Greenhouse gases									
BGHGB [6]	1.26^{b}	1.14^{ab}	0.84^{a}	2.59^{de}	2.45^{d}	1.98^{c}	3.87^{f}	3.70^{f}	2.97^{e}
BGHGR [7]	0.81^{b}	0.83^{b}	0.87^{c}	0.77^{a}	0.78^{a}	0.81^{b}	0.77^{a}	0.77^{a}	0.81^{b}
NGHGB [8]	-3.42^{c}	-1.26^{e}	-1.52^{e}	-4.63^{b}	-1.30^{e}	-1.67^{de}	-7.26^{a}	-2.15^{de}	-2.65^{cd}
NGHGR [9]	1.50^{f}	1.19^{c}	1.24^{d}	1.42^{e}	1.12^{a}	1.16^{bc}	1.44^{e}	1.13^{ab}	1.17^{bc}
Energy									
NEB [10]	-3.18^{a}	15.20^{bc}	12.70^{b}	-3.40^{a}	24.92^{d}	20.60^{cd}	-0.84^{a}	42.99^{f}	35.61^{e}
NER [11]	0.73^{a}	2.53^{bc}	2.31^{b}	0.80^{a}	2.74^{c}	2.48^{b}	0.96^{a}	3.37^{e}	3.02^{d}
NEB_CP [12]	27.57^{c}	15.20^{ab}	14.77^{a}	44.09^{d}	24.92^{bc}	23.79^{abc}	72.35^{e}	42.99^{d}	40.53^{d}
NER_CP [13]	3.31^{b}	2.53^{a}	2.53^{a}	3.61^{b}	2.74^{a}	2.71^{a}	4.34^{c}	3.37^{b}	3.30^{b}
Transport service									
Vehicle kilometres [14]	10.49^{a}	11.28^{a}	10.06^{a}	16.20^{b}	17.63^{b}	15.53^{b}	24.97^{c}	27.51^{c}	23.94^{c}
Carbon emissions [15]	20.79^{d}	21.13^{d}	15.04^{abc}	17.10^{bcd}	17.99^{cd}	11.70^{ab}	14.88^{abc}	16.10^{bcd}	9.73^{a}
GHG emissions [16]	0.12^{bc}	0.10^{ab}	0.08^{a}	0.16^{e}	0.14^{cd}	0.13^{c}	0.16^{de}	0.13^{cd}	0.12^{c}
Energy demand [17]	1.14^{f}	0.88^{cd}	0.96^{de}	1.04^{e}	0.81^{bc}	0.90^{cd}	0.87^{cd}	0.66^{a}	0.74^{ab}

[1] Subsystems are coded for management intensity (1, 2, 3) and biofuel conversion process (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)). Each value in this table is the mean of three values for the respective combination of management intensity and conversion process.

[2] Ecosystem carbon balance (ECB) was calculated as sum of carbon source (+) and sink (-). Values are given in kg C ha^{-1} y^{-1}. Means diverged strongly because of the factor elevation (Figure 10). Therefore a one-way ANOVA showed no significant differences ($p = 0.5954$).

[3] Ecosystem carbon ratio (ECR) of carbon sink to source. An ECR superior to one implies carbon accumulation in the ecosystem. Means diverge strongly because of the factor elevation (Figure 10). Therefore a one-way ANOVA showed no significant differences ($p = 0.4498$).

[4] Biofuel carbon balance (BCB) as sum of carbon source (+) and sink (-). Values are given in Mg C ha^{-1} y^{-1}.

[5] Biofuel carbon ratio (BCR) of carbon sink to source. A BCB exceeding one implies a carbon sink for the subsystem.

[6] Biofuel greenhouse gas balance (BGHGB) as sum of GHG source (+) and sink (-). Values are given in Mg CO_2e ha^{-1} y^{-1}.

[7] Biofuel GHG ratio (BGHGR) of GHG sink to GHG source. A BGHGR exceeding one signifies GHG sequestration for the biofuel life cycle.

[8] Net greenhouse gas balance (NGHGB) as sum of GHG source (+) and sink (-). Values are given in Mg CO_2e ha^{-1} y^{-1}.

[9] Net GHG ratio (NGHGR) of GHG sink (including saved emissions) to GHG source. An NGHGR exceeding one implies GHG savings compared to the fossil fuel reference scenario.

[10] Net energy balance (NEB) as sum of energy inputs (-) and biofuel energy (LHV) (+). Values are given in GJ ha^{-1} y^{-1}.

[11] Net energy ratio (NER) of biofuel energy (LHV) to energy inputs. An NER higher than one marks a renewable biofuel.

[12] Net energy balance incl. co-products (NEB_CP) as sum of energy inputs (-) and energy products (+).Values are given in GJ ha^{-1} y^{-1}.

[13] Net energy ratio including co-products (NER_CP), calculated as ratio of energy inputs to all energy products.

[14] Vehicle kilometres per hectare per year with values given in vkm*10^^{3} ha^{-1} y^{-1}

[15] Life cycle carbon emissions were calculated as fraction of carbon emissions to provide one vehicle kilometre. Values are given in mg C vkm^{-1}.

[16] Life cycle GHG emissions were calculated as fraction of GHG emissions per vehicle kilometre. Values are given in kg CO_2e vkm^{-1}.

[17] Non-renewable energy demand of transport service was defined as the amount of non-renewable energy required to provide one vehicle kilometre. Values are given in MJ vkm^{-1}.

3.6. Sustainability criteria for biofuel subsystems

Criteria for a sustainable production of second-generation biofuels from grassland biomass as stated in the introduction (‘Permanent grassland biomass as biofuel feedstock’) were assessed for biofuel life cycles aggregated for the factors management intensity and conversion process (Table 8).

Table 8: Sustainability criteria for grassland biofuel life cycles aggregated for the factors management intensity and conversion process.

Subsystems [1]	1c	1g	1f	2c	2g	2f	3c	3g	3f
Extent of production system [2]	small	medium	large	small	medium	large	small	medium	large
Nitrogen input [kg ha^{-1} y^{-1}]	20 to 25	20 to 25	20 to 25	70 to 80	70 to 80	70 to 80	110 to 120	110 to 120	110 to 120
Production pathway	CHP	Bio-SNG	LC-etOH	CHP	Bio-SNG	LC-etOH	CHP	Bio-SNG	LC-etOH
End use technology	electric car	car bio-SNG	car ethanol	electric car	car bio-SNG	car ethanol	electric car	car bio-SNG	car ethanol
Conflict with food security [3]	low	low	low	medium	medium	medium	medium	medium	medium
Conflict with water availability [4]	none	none	medium	low	low	medium	low	low	medium
Conflict with biodiversity [5]	none/little	none/little	none/little	low	low	low	medium	medium	medium
Quality of habitat protected [6]	high	high	high	medium	medium	medium	medium	medium	medium

[1] Subsystems are coded for management intensity (1, 2, 3) and biofuel conversion process (c = combustion (CHP), G = gasification (bio-SNG), and, f = fermentation (LC-etOH)).

[2] Geographical extent of the production system is dependent upon biorefinery size and demand for feedstock. For feedstock supply to biorefineries ten farms in case of combustion, 30 farms in case of gasification and 75 farms in case of fermentation scenarios were modelled. (Table A4).

[3] Conflicts with food security are low if grasslands are no longer used for production of hay as cattle feed. Nevertheless, conflicts with food security may arise for grasslands with higher yield potential.

[4] Conflicts with water availability may arise as more intensively farmed grasslands, mainly in lowland areas, have to be irrigated in case of drought. Research projects are currently estimating the magnitude and consequences of drought events on permanent grasslands in Austria (Eitzinger 2006). Additional water demand may arise for fermentation scenarios which require water for pre-treatment and sludge cleaning.

[5] Extensive grasslands with low management regime are important hosts of biodiversity because they create patch-shape complexity on a landscape scale (Moser, Zechmeister et al. 2002) and provide an intermediate disturbance regime (Peterseil, Wrbka et al. 2004). This effect is counteracted by rising management intensity as species richness declines with fertilizer use and more intensive management (Klimek, Kemmermann et al. 2007).

[6] Habitat quality of grasslands is dependent upon management intensity (Zechmeister, Schmitzberger et al. 2003) and fertilizer input (Klimek, Marini et al. 2008). Species richness is higher in one-cut mowing regimes, compared to more intensively managed grasslands (Niedrist, Tasser et al. 2009). Many extensive grasslands (often in one-cut or even without cutting regime) are valuable habitats for species of high conservation value (Zechmeister, Schmitzberger et al. 2003) and are therefore land-use stabilizing agricultural-environmental protection programs (Wrbka, Schindler et al. 2008).

4. Discussion

Accounting of carbon and GHG of grassland biofuels

Ecologists can contribute to life-cycle assessments by providing detailed analyses of biogeochemical cycling associated to biofuels (Davis, Anderson-Teixeira et al. 2009). Such an assessment has to include a full carbon balance of negative and positive emissions (Guinee, Heijungs et al. 2009), a GHG balance including non - CO_2 greenhouse gases (Cherubini, Bird et al. 2009), emissions from land-use change (Gnansounou, Dauriat et al. 2009; Liska and Perrin 2009) and upstream emissions from external inputs to the life cycle (Cherubini, Bird et al. 2009). This can provide the basis for a comprehensive greenhouse gas accounting of renewable energy systems (Searchinger, Hamburg et al. 2009). We here demonstrated such an assessment for second generation biofuels from grassland biomass in Austria.

According to our results, biofuels from grassland biomass are neither '*carbon-negative*', nor '*GHG negative*'. Important differences exist between an assessment accounting for carbon fluxes, ('<u>Biofuel carbon balance</u>') and an assessment including non - CO_2 greenhouse gases ('<u>Biofuel GHG balance</u>') (Crutzen, Mosier et al. 2008). Our analysis showed that an intensive grassland management was most efficient with respect to carbon emissions during the biofuel life cycle (Table 7). From a GHG perspective, however, an extensive management is by far more efficient in keeping GHG emissions low, because of smaller fertilizer-related emissions (Figure 21, Table 7).

A strongly negative NEE (net ecosystem exchange) of CO_2 constituted the biggest flux of carbon and GHG from the atmosphere to the ecosystem, but sparsely studied for Austrian grasslands (Wohlfahrt, Anderson-Dunn et al. 2008; Wohlfahrt, Hammerle et al. 2008). It will therefore be important to put more efforts into the research of net ecosystem exchange of permanent grasslands in the future, also because permanent grasslands are increasingly employed for biogas production (Prochnow, Heiermann et al. 2009). These studies should target effects of nitrogen fertilizer input and harvest on net ecosystem CO_2 exchange and changes in soil organic carbon stocks of permanent grasslands under various management intensities. This would help to provide data for a flux-based accounting of biofuel and bioenergy life-cycles and optimise grassland management for stabilisation or increase of soil organic carbon stocks. The contribution of methane to the GHG uptake of grassland used for biofuel production was found to be very low. The methane flux could, in case of wet grasslands, even become part of the GHG source.

The values for the carbon and GHG sources in this study can be interpreted as conservative estimates, i.e. GHG fluxes have not been underestimated. First, although usually not included, biomass losses (CO_2e_harvest loss; and CO_2e_loss baling) were modelled to be 20 % of gross harvest, thereby causing a relatively large biofuel GHG source of about 15 %. Second, the displacement bonus (CO_2e_dg) for biofuels was calculated with an emission factor for an ‘Euro 5 petrol car’ (0.213 kg CO_2e vkm^{-1} (Jungbluth, Chudacoff et al. 2007)), which is lower than that for emissions of an average European car in 2010 (0.240 kg CO_2e vkm^{-1} (Spielmann, Bauer et al. 2007)) or emissions for a petrol car (0.237 kg CO_2e vkm^{-1} (Gnansounou, Dauriat et al. 2009)). Third, emissions from provision of farm machinery were calculated with lower life-expectancies than in other studies (Tilman, Hill et al. 2006). Greenhouse gas emissions from fertilizer input were calculated assuming a release of 1% of the fertilizer input as N_2O (Klein, Novoa et al. 2008), yielding results comparable to annual budgets of N_2O measured for similar temperate grasslands (Soussana, Allard et al. 2007). However, temperate grasslands may exhibit, especially in case of extensive grassland management, balanced N_2O fluxes (Neftel, Flechard et al. 2007), or even may act as sink for atmospheric N_2O (Flechard, Neftel et al. 2005).

As biogenic carbon fluxes were found to be prominent in the carbon and GHG balance and as fertilizer related emissions were the main differentiating factor between carbon and GHG balance, future biofuel assessments should correctly trace biogenic carbon fluxes (Rabl, Benoist et al. 2007) and N_2O emissions.

GHG reduction potential of grassland biofuels

To assess the GHG reduction potential of grassland biofuels, results from the change-oriented net GHG balance (‘Avoided emissions - Net greenhouse gas balance’) were scaled up for the entire area of permanent grassland in Austria (Table 9). This potential is significant, and would have been bringing Austria between 8 and 26 percent closer to its Kyoto target in 2007. Although this calculation excluded possible conflicts with animal husbandry and an assessment of the demand for thermal energy (as relevant for the CHP scenario), it showed that biofuels from lignocellulosic feedstock can contribute a significant share to a future GHG extensive energy supply in Austria.

Table 9: GHG saving potential for grassland biofuels in Austria.

		CHP		Bio – SNG		LC-etOH	
Land use	Area [ha x 10^3]	Emissions saved [4] [Gg CO_2e]	Kyoto surplus [5] [%]	Emissions saved [4] [Gg CO_2e]	Kyoto surplus [5] [%]	Emissions saved [4] [Gg CO_2e]	Kyoto surplus [5] [%]
One-cut [1]	28	96	0.5	35	0.2	43	0.2
Two-cut [2]	269	1 248	6.5	351	1.8	449	2.3
Three-cut [3]	509	3 696	19.3	1 096	5.7	1 351	7.0
Sum	806	5 040	26.3	1 481	7.7	1 843	9.6

[1] Sum of grasslands in one-cut management regime and grasslands currently stabilized by agricultural-environmental schemes, amounted to about 28 x 10^3 ha in 2007 (BMLFUW 2008).

[2] Grasslands in two-cut management regime amounted to about 269 x 10^3 ha in 2007 (BMLFUW 2008).

[3] The area of grasslands with three or more cuts per year amounted to about 509 x 10^3 ha in 2007 (BMLFUW 2008). Yields may actually be higher for these grasslands as they would (partially) allow a more intense management regime.

[4] Means of net GHG balances for conversion processes and management intensities were scaled up by total available grassland area per management intensity. Values show saved emissions per year [Gg CO_2e y^{-1}] compared to the fossil reference and additional savings from: thermal energy substituting heating with light oil and production of electricity substituting the Austrian electricity mix ('Avoided Emissions – Net Greenhouse Gas Balance').

[5] In 2007 Austria emitted 19 200 Gg CO_2e more than the average emissions defined as Kyoto target (Anderl, Bednar et al. 2009). Percentages were calculated as fraction of these 'Kyoto surplus emissions' as comparison for the reduction potentials of grassland biofuels to the current Kyoto target.

Compared to GHG emissions of an average European petrol car in 2010 (Spielmann, Bauer et al. 2007), biofuels from grassland biomass were able to significantly reduce GHG emissions per vehicle kilometre (Figure 47). These reductions ranged between 33 (± 3) and 65 (± 4) % and are comparable to other renewable transport fuels such as biogas from wet fermentation (Jungbluth, Chudacoff et al. 2007) or 85 % blend of bioethanol (Gnansounou, Dauriat et al. 2009). This index base of a fossil fuel reference may be even more GHG intensive, as life cycle assessments of fossil fuels usually exclude emissions related to military operations for maintaining access to crude oil (Liska and Perrin 2009) and GHG emission of fossil fuel provision is expected to increase in future, if fuel production shifts to low-quality petroleum resources and synthetic petroleum substitutes (Brandt and Farrell 2007).

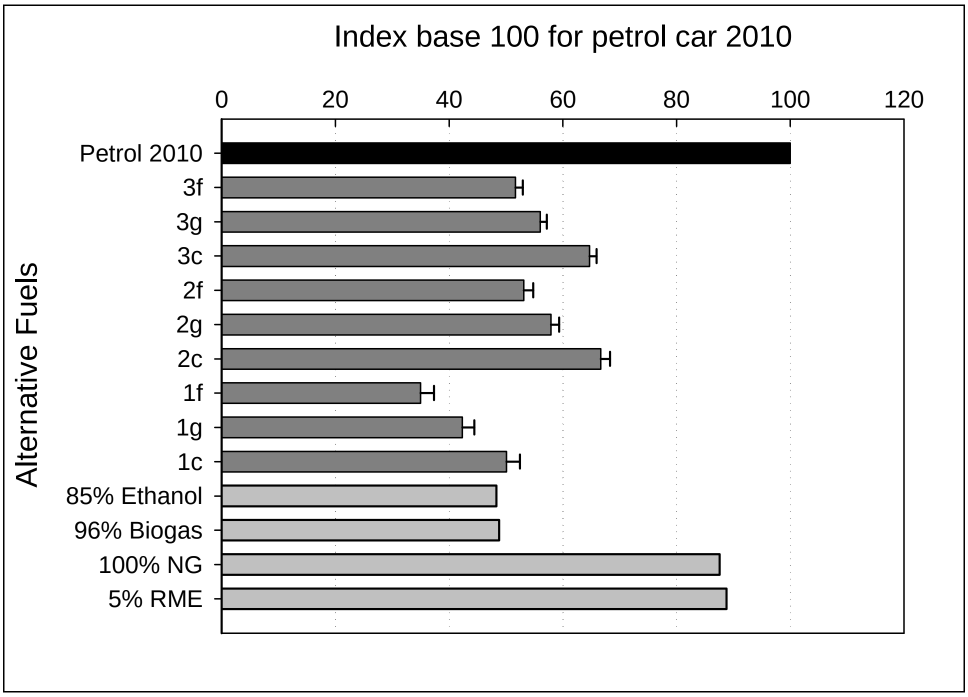

Figure 47: GHG emissions per vehicle kilometre for the average European petrol car in 2010 (= 100 %), grassland biofuels and alternative fuels. Bars are GHG emissions per vehicle kilometre as percentage of GHG emissions of an average European petrol car in 2010 (black, taken Ecoinvent 2.1 (Spielmann, Bauer et al. 2007)). Grassland biofuels (dark gray) are coded by management intensity (1, 2, 3 for cutting frequency) and biofuel conversion process (c = combustion (CHP), g = gasification (bio-SNG), f = fermentation (LC-etOH)); error bars are standard errors of means. Alternative fuels (gray) are: 85 % Ethanol blend (Gnansounou, Dauriat et al. 2009); 96 % Biogas; 100 % Natural Gas; 5 % Rapeseed Methyl Ester are taken from Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007).

Additionally there is a potential to further reduce GHG emissions of grassland biofuels. Especially the reduction of fertilizer-related emissions (fertilizer provision and direct N_2O emissions) could be promising for such an undertaking. On the level of grassland management timing, amount and type of fertilizer application are important variables for keeping of N_2O emissions low. Nitrogen fertilizer input could also be reduced by coupling biofuel production to the use of anthropogenic wastes (Antizar-Ladislao and Turrion-Gomez 2008) or animal manure (Cherubini, Bird et al. 2009), which would at least lower GHG emissions from fertilizer provision. Furthermore, enriching the grassland's with nitrogen fixing legumes (Tilman, Hill et al. 2006) such as clover may reduce fertilizer demand in low-input high-diversity grasslands (Weigelt, Weisser et al. 2009). In fermentation and gasification pathways, a recycling of nitrogen could significantly lower the demand for external nitrogen inputs (Anex, Lynd et al. 2007). It is evident that a reduction in mineral fertiliser inputs would as well lower external energy demand for biofuel production, thereby improving energy balances and environmental performance of grassland biofuels.

Energy conversion efficiency of grassland biofuels

Values for net energy balance were positive for biofuels from gasification and fermentation pathways, whereas combustion pathways showed negative net energy balances because of smaller energy outputs in form of electricity. As electrical energy can be more efficiently used to propel cars (Campbell, Lobell et al. 2009; Ohlrogge, Allen et al. 2009), the transport services of the three production pathways were comparable in vehicle kilometres per unit of land (Table 7). Net energy balances including co-products were positive for all life cycles with highest values for combustion subsystems. Energetic co-products are therefore important to account for in the assessment of overall energy conversion efficiency of biofuel production pathways.

We compared '*net energy ratio*' or '*energy return on investment*' (Costanza and Cleveland 2006; Hammerschlag 2006) of second generation biofuels as LCA studies account for the calorific value of biofuel products in different ways (lower heating value or higher heating value) and allocation methods for energy co-products are not fully resolved (Gnansounou, Dauriat et al. 2009). Net energy ratios for Austrian grassland biofuels were rather modest compared to international references (Table 10). This reflects that grassland management in Austria is an energy and input intensive land use compared to the U.S. American or Brazilian context because of small average farm size, farm machinery, topography, and climate constraints. The energy embodied in farm machinery was found to be significantly higher for grassland management systems (6.97 GJ ha^{-1} y^{-1} ± 0.68) than in other studies (0.19 GJ ha^{-1} y^{-1} in (Tilman, Hill et al. 2006) and 4.7 GJ ha^{-1} y^{-1} in (Schmer, Vogel et al. 2008)). Additionally, grasslands in Austria can be more fertilizer intensive (fertilizer input of 20 to 120 kg N ha^{-1} y^{-1} caused about 25 % of total energy input) than other lignocellulosic energy crops, such as prairie grasslands with no nitrogen fertilizer input (Tilman, Hill et al. 2006). Net energy ratios of grassland biofuels (Table 10) exceed ratios of many first generation biofuels, which, in case of corn grain ethanol, range from 0.84 to 1.62 (Hammerschlag 2006) and for soybean biodiesel amount to 1.93 (Hill, Nelson et al. 2006).

Table 10: Energy ratios of selected second-generation biofuels.

Biofuel	Co-product	ER [1]	Feedstock	Reference
Electricity	Thermal energy	3.31	Grassland, one-cut	NER_CP (Table 7)
Electricity	Thermal energy	3.61	Grassland, two-cut	NER_CP (Table 7)
Electricity	Thermal energy	4.34	Grassland, three-cut	NER_CP (Table 7)
Biomass electricity	None	5.51	Prairie grassland	(Tilman, Hill et al. 2006)
Bio-SNG	None	2.53	Grassland, one-cut	NER_CP (Table 7)
Bio-SNG	None	2.74	Grassland, two-cut	NER_CP (Table 7)
Bio-SNG	None	3.37	Grassland, three-cut	NER_CP (Table 7)
Synfuel	Electricity	8.09	Prairie grassland	(Tilman, Hill et al. 2006)
LC-etOH	Electricity	2.53	Grassland, one-cut	NER_CP (Table 7)
LC-etOH	Electricity	2.71	Grassland, two-cut	NER_CP (Table 7)
LC-etOH	Electricity	3.30	Grassland, three-cut	NER_CP (Table 7)
LC-etOH	Electricity	4.55	Poplar	Lynd & Wand (2004) in (Hammerschlag 2006)
LC-etOH	Electricity	4.4	Corn stover	Sheehan et. al. (2004) in (Hammerschlag 2006)
LC-etOH	Electricity	5.44	Prairie grassland	(Tilman, Hill et al. 2006)

[1] Energy ratio was calculated as ratio of sum of energy products to energy inputs.

Energy efficiency of grassland biofuels was benchmarked with other second generation biofuel chains (Table 11) using results obtained for net energy balance including co-products ('Net energy balance with co-products'). In terms of energy yield, Austrian grassland biofuels are comparable to other second generation biofuels from lignocellulosic feedstock.

Table 11: Energy yield of selected second-generation biofuels.

Biofuel	Co-product	Energy yield [1]	Feedstock	Reference
Electricity	Thermal energy	27.6 (± 3.5)	Grassland, one-cut	NEB_CP (Table 7) [2]
Electricity	Thermal energy	44.1 (± 3.4)	Grassland, two-cut	NEB_CP (Table 7) [2]
Electricity	Thermal energy	72.4 (± 6.3)	Grassland, three-cut	NEB_CP (Table 7) [2]
Biomass electricity	None	18.1	Prairie grassland	(Tilman, Hill et al. 2006)
Bio-SNG	None	15.2 (± 2.1)	Grassland, one-cut	NEB_CP (Table 7) [2]
Bio-SNG	None	24.9 (± 2.1)	Grassland, two-cut	NEB_CP (Table 7) [2]
Bio-SNG	None	43.0 (± 4.0)	Grassland, three-cut	NEB_CP (Table 7) [2]
Synfuel	Electricity	28.4	Prairie grassland	(Tilman, Hill et al. 2006)
LC-etOH	Electricity	14.8 (± 2.0)	Grassland, one-cut	NEB_CP (Table 7) [2]
LC-etOH	Electricity	23.8 (± 2.0)	Grassland, two-cut	NEB_CP (Table 7) [2]
LC-etOH	Electricity	40.5 (± 3.7)	Grassland, three-cut	NEB_CP (Table 7) [2]
LC-etOH	Electricity	17.8	Prairie grassland	(Tilman, Hill et al. 2006)
LC-etOH	Electricity	24.6	Poplar	Lynd & Wand (2004) in (Hammerschlag 2006) [3]
LC-etOH	Electricity	23.2	Corn stover	Sheehan et. al. (2004) in (Hammerschlag 2006) [3]
LC-etOH	None	60	Switchgrass	(Schmer, Vogel et al. 2008) [4]

[1] Energy yield refers to the energy product (LHV preferably), including possible co-products [GJ ha^{-1} y^{-1}].

[2] Values of this study ('Net energy balance') are based on lower heating value for methane and ethanol. Numbers shown in this table are means farms for conversion processes and management intensities. Standard deviations of three values are shown in brackets.

[3] Values were amended from HHV to LHV to be comparable to this study's results.

[4] Mean 'net energy yield' of four switchgrass (Panicum virgatum) trial farms in the U.S. mid-west (Schmer, Vogel et al. 2008). The supporting online material of this publication does not refer to heating values used in the study, thus it is unclear if presented values relate to higher or lower heating value.

Comparing the amount of non-renewable energy used to provide one vehicle kilometre of transport service, grassland biofuels are, with values ranging from 0.66 (± 0.02) to 1.14 (± 0.05) MJ km^{-1}, less energy demanding than the reference of an average European petrol car in 2010 (Spielmann, Bauer et al. 2007) (Figure 49). Wet fermentation of biomass to biogas (Jungbluth, Chudacoff et al. 2007) and 85 % blend of bioethanol (Gnansounou, Dauriat et al. 2009) exhibited comparable non-renewable energy demand per vehicle kilometre.

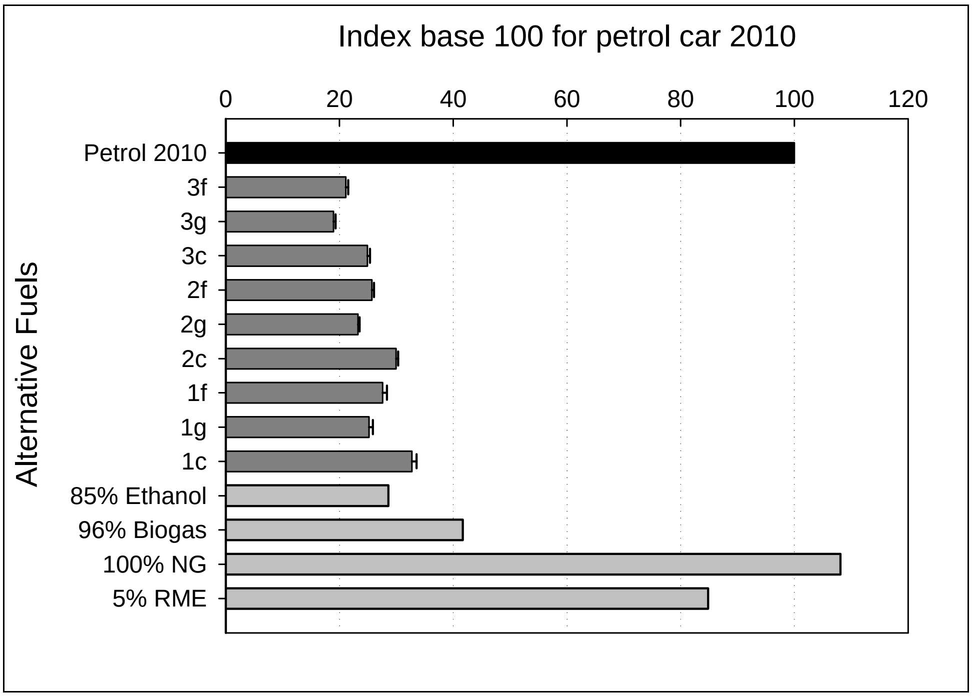

Figure 48: Non-renewable energy demand per vehicle kilometre for an average European petrol car in 2010 (= 100 %), grassland biofuels and alternative fuels. Non-renewable energy demand per vehicle kilometre is given as percentage of an average European petrol car in 2010 (black, taken from Ecoinvent 2.1 (Spielmann, Bauer et al. 2007). Grassland biofuels (dark gray) are coded by management intensity (1, 2, 3 for cutting frequency) and biofuel conversion process (c = combustion (CHP), g = gasification (bio-SNG), f = fermentation (LC-etOH)); error bars are standard errors of means. Alternative fuels (gray) are: 85 % Ethanol blend (Gnansounou, Dauriat et al. 2009); 96 % Biogas; 100 % Natural Gas; 5 % Rapeseed Methyl Ester are taken from Ecoinvent 2.1 (Jungbluth, Chudacoff et al. 2007).

Implications for land use

The present study also aimed at elucidating differences between an intensive (high-input) and an extensive (low-input) grassland management system in terms of carbon, GHG and energy balances. In principle, extensive grasslands show higher biodiversity than intensive grassland plots (Table 8), which suggests a gradient from 'low-input, high diversity' to 'high-input, low diversity' (Tilman, Hill et al. 2006) systems, corresponding to levels of cutting frequency and fertilizer inputs. We found that this gradient was related to differences in carbon, GHG and energy fluxes, with implications for land use.

Our results (Table 7) revealed lower carbon recycling ratios (ECR and BCR) for grasslands managed with low inputs. Contrasting to that, extensive grasslands were significantly more effective in fixing greenhouse gases than intensively managed grassland plots as reflected in the BGHGR. The effectiveness of reducing greenhouse gases, as quantified in the NGHGR, was higher, though not significantly, for low-input systems. Extensive grassland plots allowed – across all conversion pathways - the least GHG intensive transport service. Concerning energy conversion efficiency, biofuel life cycles exhibited higher net energy ratios (NER and NER_CP) in more intensively managed grasslands (Table 7). This trend, i.e. that energy and carbon efficiency is highest for intensive grasslands, while GHG saving potentials (calculated e.g. as the net GHG ratio) were highest for extensive grasslands, was found as well for carbon emissions, GHG emissions and non-renewable energy demand per vehicle kilometre (Table 7). Thus, low-input systems may allow biofuels with the most effective greenhouse gas reduction potential (as reflected in the metrics BGHGR and NGHGR) but cannot compete with net GHG savings per unit of land (calculated in the NGHGB) or energy yields (NEB and NEB_CP) of more intensively managed grasslands. Therefore, the main tradeoff for grassland biofuels was found between carbon sequestration, efficient GHG mitigation and maximized energy yield. However, all investigated biofuel production systems lessened GHG emissions of transport services compared to a fossil fuel reference (Figure 47) and hence would all be suited to mitigate GHG emissions within the transport sector.

Since the production of grassland biomass as biofuel feedstock is expected to have implications on land use, policymakers will have to address farmers as the main stakeholders of land use decision-making processes (Penker and Wytrzens 2005). Therefore, the results of this study were aggregated to a farm level to provide an applied land use perspective (Table 12). Transport services from renewable resources could be a possible agricultural product produced by farmers. Yields of biofuel life cycles were therefore compared for the modelled farms (Table A1). The amount of transport services produced per farm were significantly different for the three farm types modelled, exhibiting greater variance between the farms than between the conversion processes, reflecting differences among the farms in average slope, grassland productivity and distribution and management intensity of meadows at different elevations.

Table 12: Total transport service of conversion processes for three model farms.

	Transport services [km x 10^3 farm^{-1} y^{-1}] *			Transport services [persons transported farm^{-1} y^{-1}]¥		
	CHP	Bio-SNG	LC-etOH	CHP	Bio-SNG	LC-etOH
Mountain farm	163	179	157	19	21	18
Hillside farm	180	198	173	21	23	20
Valley farm	210	230	201	25	27	24

* Transport service for the total farm area of nine hectares. Differences among the farms in terms of average slope of land use plots, management intensity and grassland productivity were modelled (Table A1).

¥ Calculated with the average distance driven in Austria per capita (8486 km) in 2003 (BMVIT 2007). The values are corresponding to the amount of persons that can be provided with transport services per farm and year

To discuss the performance of the biofuel conversion pathways in terms of carbon recycling potential (BCR), GHG reduction potential (NGHGR) and energy conversion efficiency (NER_CP), these three metrics were compared to each other at a farm level (Figure 49). In this evaluation, combustion of grassland biomass showed the most beneficial energy conversion efficiency and GHG reduction potential, whereas carbon recycling potential was in between the two other conversion processes. Lignocellulosic fermentation was most beneficial for carbon recycling, while GHG reduction potential and energy conversion efficiency were in the lower range of the three processes. Gasification of biomass was the least efficient process modelled for all three indicators.

To assess potential of grassland biofuels in Austria, results for transport services per unit of land were scaled up for the total area of permanent grassland in Austria (Table 13). In this extreme land use scenario, grassland biofuels would be able to substitute about 25 % of the fossil fuel used for passenger transport in Austria in 2005 (BMVIT 2007). Here, the same delimitations remain as discussed before (Table 9). This scenario, however unlikely it is, demonstrates that biofuel production from grassland feedstocks could realistically supply a significant proportion of transport services in Austria. On a European scale, it was predicted that large areas of surplus land will be available in the future (Rounsevell, Reginster et al. 2006), which may be used for production of lignocellulosic biofuel feedstock such as grassland biomass.

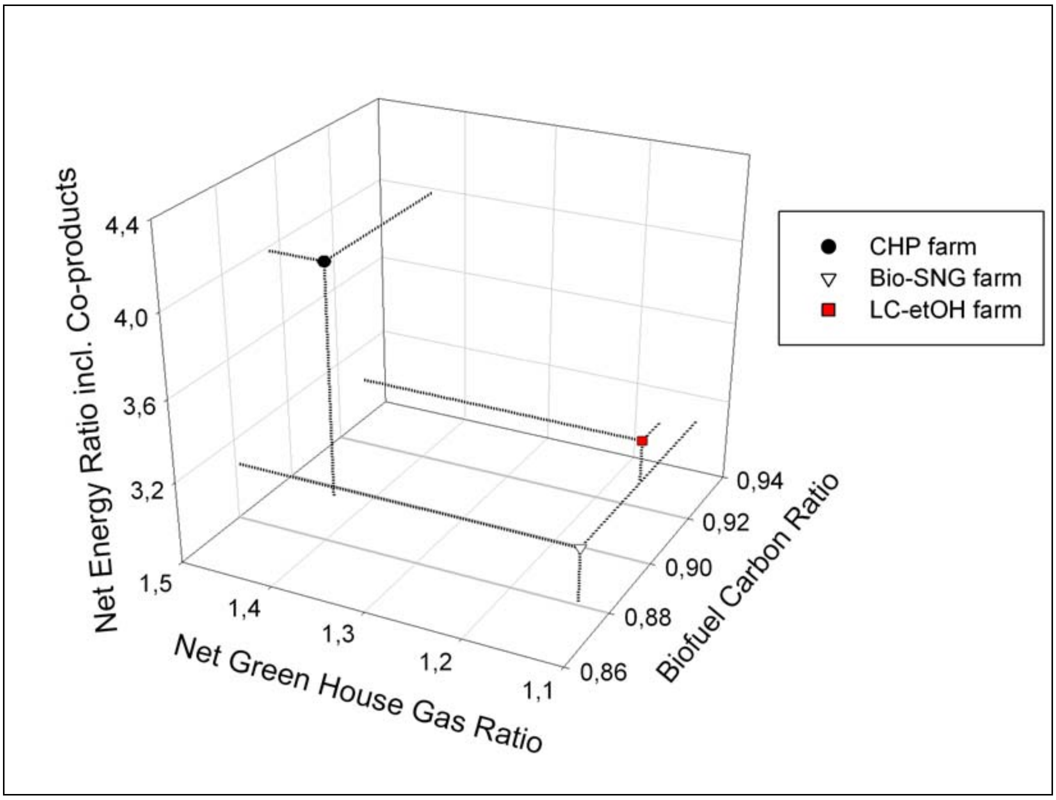

Figure 49: Carbon recycling potential (BCR), GHG saving potential (NGHGR) and energy conversion efficiency (NER_CP) compared at a farm level. Values given are means calculated from BCR, NGHGR and NER_CP on a farm level and referenced for conversion processes (combustion (CHP), gasification (bio-SNG), and fermentation (LC-etOH)). Ratios were weighted for extent of land use plots within the total area of grassland per model farm.

Table 13: Potential transport service of grassland biofuels in Austria.

	CHP		Bio – SNG		LC-etOH	
Land use	Transport service [pkm x 10^6] [1]	% 2005 [2]	Transport service [pkm x 10^6] [1]	% 2005 [2]	Transport service [pkm x 10^6] [1]	% 2005 [2]
One-cut [3]	347	0.4	373	0.5	333	0.4
Two-cut [4]	5 146	6.3	5 602	6.8	4 935	6.0
Three-cut [5]	14 999	18.3	16 525	20.1	14 384	17.5
Sum	20 492	24.9	22 501	27.4	19 652	23.9

[1] Means of transport service per hectare per year for conversion processes and management intensities were scaled up by total available land area (see below). To calculate passenger kilometres for Austria, values for transport kilometre were multiplied by the Austrian manning factor of 1.18. Values are shown in passenger kilometres per year [pkm y^{-1}].

[2] In 2005 total Austrian passenger transport (excluding freight) amounted to 82148 x 10^6 passenger kilometres (BMVIT 2007).

[3] One-cut grasslands and grasslands stabilized by agri-environmental schemes, amounted to about 28 x 10^3 ha in 2007 (BMLFUW 2008).

[4] Grasslands in two-cut management regime amounted to about 270 x 10^3 ha in 2007 (BMLFUW 2008).

[5] The area of grasslands with three or more cuts per year made up for about 510 x 10^3 ha in 2007 (BMLFUW 2008).

Sustainable second generation biofuels from grassland biomass

We showed in this study that a biofuel production from grassland biomass via second generation biofuel platforms can be sustainable from a carbon, GHG and energy point of view, especially if compared to a fossil fuel reference. This is in line with other studies (Tonn, Thumm et al. 2008; Rosch, Skarka et al. 2009) stating the possibility of sustainably using grassland biomass for bioenergy production. However, we also try to assess additional indicators biofuel sustainability of permanent grasslands (Table 8).

In terms of biodiversity and nature conservation, low-input grasslands (one-cut mowing regimes) offered the greatest benefits. However, to avoid depletion of soil organic carbon pools (Anderson-Teixeira, Davis et al. 2009), grasslands need to be managed according to edaphic and topographic factors, which may include the need to fertilize. A sustainable land use at the landscape level will therefore always include a variety of grassland management intensities. To shun competition with food production, biofuel production will most likely be restricted to lower input grasslands, while intensively managed grasslands may be used to produce high-quality biomass as animal feed or, in times of excess production, biofuel feedstock. Thereby farmers would have more options to use grasslands, with biofuel feedstock production possibly providing an additional income.

Second generation biofuel pathways require different amounts of lignocellulosic feedstock which lead to differences in hinterland necessary to supply the biorefineries (Table A4), which demonstrates the necessity to address questions of scale explicitly. This aspect can only be discussed to a limited extent in this work, but seems important for future research. Combustion of biomass in a Stirling unit for combined heat and power proved to be valuable at the small scale which offers advantages especially for alpine regions where feedstock transport can be problematic. Such a scenario extends the concept of farmers as energy producers to farmers providing transport service and energy on a local scale. Combustion of biomass to produce transport services by electrical mobility can be less area demanding than other second generation biofuels because of greater efficiency of the electrical engine compared to an internal combustion engines (Ohlrogge, Allen et al. 2009). Gasification of biomass with subsequent methanation and the use of methane to propel cars is the scenario with the largest spatial requirements to produce biofuel feedstock. This scenario may be applied in cases where transport routes already exist, enabling the transport of feedstock to large gasification-methanation facilities. However, as grassland biomass may not be available at all time or may not be sufficient to fully supply a large-scale gasification plant, a diversification of lignocellulosic feedstocks would be required in this scenario. Because methane is an energy carrier which can be beneficially used to propel cars (Winter 2008) and to power energy systems already in place, this conversion is promising as an immediate biofuel option. Fermentation of biomass, on the other hand, can be described as scenario with an intermediate spatial extent. Nonetheless, much research is needed to improve ethanol fermentation (Hamelinck, van Hooijdonk et al. 2005; Wyman 2007; Lynd, Laser et al. 2008), to meet those efficiencies modelled in our study. However, lignocellulosic fermentation offers advantages in terms of carbon recycling, nitrogen recovery potential and mix of energetic products (ethanol and electricity), making fermentation an interesting biofuel pathway. This holds true not only for grassland biomass as feedstock but also for other lignocellulosic feedstock such as wood.

Achieving energy independence and greenhouse gas mitigation by the use of renewable resources will not be feasible by producing biofuel alone. Additionally, a mix of conversion processes will be needed to optimise biofuel productions and it is likely that all pathways will find their niche in a future renewable energy supply because of distinct advantages in providing transport service and energy supply from domestic resources. However, before realizing such strategies, a spatially explicit modelling of biofuel scenarios (Hellmann and Verburg 2008) should assess the effects of bioenergy production at the landscape scale. Thereby biofuel strategies can be adapted to local conditions to maximize benefits of climate change mitigation, energy security, biodiversity conservation and farm income (Antizar-Ladislao and Turrion-Gomez 2008).

Some opportunities arise from the present assessment on a landscape scale for the use of grassland biomass as feedstock for biofuel production. Given that low-input grasslands can supply lignocellulosic feedstock without altering land-use practises, biofuels from grassland biomass can be a strategy to stabilize land use for the conservation of semi-natural grasslands (Lindborg, Bengtsson et al. 2008). Additionally, areas that have recently been abandoned and are now starting to re-forest, have the potential to be managed as grasslands in a GHG extensive way to enhance biodiversity at a landscape level. Similarly, the conversion of cultivated land to permanent grassland may provide benefits of enhanced SOC accumulation (Anderson-Teixeira, Davis et al. 2009) and augmented biodiversity. As shown in this work, lignocellulosic biofuels can be produced from grasslands in a variety of management intensities which can provide an opportunity to maintain diversity within grassland ecosystems (Klimek, Marini et al. 2008). Thereby a sustainable '*heterogeneous production landscape*' (Fischer, Lindenmayer et al. 2006), featuring various land use types (Haberl, Wackernagel et al. 2004), can be created by the integration of grassland patches into a diverse agricultural land use matrix (Fischer, Lindenmayer et al. 2006).

Conclusion

Albeit second generation biofuel from permanent grassland in Austria were found to be carbon and GHG positive, they all offered a significant GHG reduction potential compared to fossil fuels. A thorough evaluation of biogenic carbon fluxes was identified to be crucial for such an assessment as they significantly affected carbon and GHG balances and were in general poorly constrained. Energy balances of grassland biofuels were also positive and comparable to other second generation biofuels, showing the importance of including co-products in energy assessments of biofuels. We conclude that a life cycle assessment of biofuels should be strictly flux-based, should include a change-oriented approach to assess GHG saving potential and should include a quantification of environmental costs of transport services.

Developing a diversity of biofuel pathways will be crucial to successfully adapt second generation biofuel technology in an environmentally sound manner. Methane production via synthesis gas or lignocellulosic fermentation were found to be promising scenarios for a long-term perspective, but still need further research efforts to realize their full potentials. This work further corroborated the potential for electrical mobility within a decentralized combined heat and power system fed by lignocellulosic feedstock. If Austria wants to successfully compete in the renewable energy sector, future research projects should target all biofuel conversion processes presented here, including other lignocellulosic feedstock.

Our study found the main tradeoff for biofuel production in the optimization of grasslands for carbon sequestration and energy conversion efficiency on the one side and effectiveness of GHG mitigation on the other. Low-input grasslands provided the highest greenhouse gas savings (highest NGHGR and BGHGR), while high-input grassland allowed for the highest energy efficiency, carbon recycling potential and greenhouse gas saving per unit of land (highest NEB, BCR, NGHGB). Nevertheless, all investigated life cycles exhibited energy gains and a potential GHG reduction, compared to the current situation.

The scenarios for biofuel production that we developed could also be a strategy to maintain grasslands and their importance for landscape diversity. Additionally, income opportunities for farmers arise from these scenarios with renewable transport services as novel agricultural product. Biofuels from grassland biomass could therefore help to marry GHG mitigation, energy security, rural development and nature conservation goals. Second-generation biofuels thus bear significant potentials to contribute in a future, GHG extensive energy system by sustainably providing transport services from domestic lignocellulosic feedstock such as grassland biomass.

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Appendices

Table A1: Parameters of model farms

Farm	Valley			Hillside			Mountain			comment	Reference
Elevation above sea level [m]	650-800			800-1100			1100-1300				INVEKOS (Schaumberger 2009)
Cutting frequency [cuts*y^{-1}]	1	2	3	1	2	3	1	2	3		
Area [ha]	0.7	2.3	6.0	1.0	3.1	4.9	1.3	3.6	4.1	9 ha grassland per farm.	INVEKOS (Schaumberger 2009)
Area [% of total grassland area]	7.8	25.6	66.7	11.1	34.4	54.4	14.4	40.0	45.6		INVEKOS (Schaumberger 2009)
Area >25 % mean slope [% of plot]	64	67	82	50	50	61	28	34	35		INVEKOS (Schaumberger 2009)
Area 25-35 % mean slope [% of plot]	21	23	13	24	27	24	28	30	32		INVEKOS (Schaumberger 2009)
Area 35-50 % mean slope [% of plot]	15	10	5	26	23	15	44	36	34		INVEKOS (Schaumberger 2009)
NEE [kg CO_2-C ha^{-1} y^{-1}]	-1700	-2500	-3700	-1400	-2200	-3500	-1400	-2200	-3200	Compare Table A6	(Ammann, Flechard et al. 2007; Gilmanov, Soussana et al. 2007)
DOC leaching [kg C ha^{-1} y^{-1}]	40	45	50	45	50	55	50	55	60	Compare Table A5	(Klumpp, Soussana et al. 2007)
CH_4 uptake (oxidation) [kg CH_4-C ha^{-1} y^{-1}]	2.25	2.87	1.5	2.25	2.87	1.5	2.25	2.87	1.5	Compare Table A7	(Boeckx and Van Cleemput 2001)
Gross harvest [kg DM ha^{-1} y^{-1}]	3750	5625	8750	3125	5000	8125	3125	5000	7500	Before harvest and baling losses.	(Buchgraber 2000)
N-input [kg N ha^{-1} y^{-1}]	25	75	110	20	70	115	25	80	120	modelled after Austrian standard grassland management practise	(BMLFUW 2006)

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Table A2: Modelled grassland biomass

Farm	Valley			Hillside			Mountain			comment	Source
Elevation above sea level [m]	650-800			800-1100			1100-1300				
Cutting frequency [cuts*y-1]	1	2	3	1	2	3	1	2	3		
Biomass Parameters											
Carbon content (% TM)	44	43	42	44	43	42	44	43	42	Based on values in Table A3	
Raw fibre content (g kg TM-1)	350	310	260	320	300	250	310	290	240		(Buchgraber 2009)
Raw Protein content (g kgTM-1)	80	120	140	90	110	130	90	100	120		(Buchgraber 2009)
Lower heating value (MJ kg-1)	16.8	16.6	16.4	16.8	16.6	16.4	16.8	16.6	16.4	Based on values in Table A3	

Table A3: Grassland biomass

Biomass description	**Remarks**	**Carbon (wt.%)**	**Ash (wt%)**	**Higher heating value (MJ kg-1)**	**Lower heating value (MJ kg-1)**	**Source**
Grass	Analysis done by TU Wien; data from BIOBIB database	46.4 (dry)	8.4 (dry)	18.185 (dry)	17.041 (dry)	http://www.ecn.nl/phyllis ID: 613
Grass from nature reserve	Grasses (and plants) from Wieden, the Netherlands.	45.6 (dry)	6.8 (dry)	18.240 (dry)	16.909 (dry)	http://www.ecn.nl/phyllis ID: 1855
Grass, field grass	The calorific value and the elementary analysis refers to dry biomass.	46.31 (dm)	9.35 (dm)	18.412	17.249	http://www.vt.tuwien.ac.at/biobib/fuel98.html ID: 39. grass, field grass
Grass, intensive grass	The calorific value and the elementary analysis refers to dry biomass.	45.11 (dm)	9.93 (dm)	18.13	17.053	http://www.vt.tuwien.ac.at/biobib/fuel100.html ID: 41. grass, intensive grass
Landschaftspflegeheu		-	5.36 (3.6 – 7.5)	-	17.56	In: (Oechsner 2008) Quoted from: Hartmann, H., Böhm, Th. u. L. Maier, 2000: Naturbelassene biogene Festbrennstoffe – umweltrelevante Eigenschaften und Einflussmöglichkeiten, Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen, Materialien 154, S. 57-87, 122ff, München, Sept. 2000
Federseeheu		46.9	5,6	-	16.6	In: (Oechsner 2008) Quoted from: Lemmer, A. u. H. Oechsner, 2001: Einsatz von Mähgut landwirtschaftlich nicht genutzter Flächen als Kosubstrat in landwirtschaftlichen Biogasanlagen, Tagungsband zur 5. Internationalen Tagung „Bau, Technik und Umwelt in der landwirtschaftlichen

						Nutztierhaltung“, Agrartechnik Universität Hohenheim (Hrsg), Stuttgart
Landschaftspflegeheu Zollernalbkreis		42.72	8.08	-	16.49	In: (Oechsner 2008) Quoted from: (Rösch, Raab et al. 2007)
Heu 1. Schlag		44.4	6.9	-	17.4	(Kiesewalter, Riehl et al. 2007)
Heu 2. Schlag		45.3	9.3	-	17	(Kiesewalter, Riehl et al. 2007)
Heufaserstoff		45.2	6.3	-	17.2	(Kiesewalter, Riehl et al. 2007)
Futterwiese intensiv, extensiv und Streuwiese	Tabelle gibt hier nur Aggregat für diese drei Grünländer an	-	5.0-9.0	-	16.4-17.4	(Rösch, Raab et al. 2007)
Ext-1	Extensive meadow, first cut	-	-	18.3	-	(Amon 2006)
Ext-2	Extensive meadow, first cut	-	-	18.7	-	(Amon 2006)
Ext-2	Extensive meadow, second cut	-	-	18.3	-	(Amon 2006)
Ext-3	Extensive meadow, first cut	-	-	19	-	(Amon 2006)
Ext-3	Extensive meadow, second cut	-	-	17.9	-	(Amon 2006)
Ext-3	Extensive meadow, third cut	-	-	18.6	-	(Amon 2006)
Int-4	Intensive meadow, first cut	-	-	19.6	-	(Amon 2006)
Int-4	Intensive meadow, second cut	-	-	19.2	-	(Amon 2006)
Int-4	Intensive meadow, third cut	-	-	19.4	-	(Amon 2006)
Int-4	Intensive meadow, fourth cut	47.5	-	19.2	-	(Amon 2006)
Int-F-3	Intensive meadow with earlier harvesting dates; first cut	-	-	19.5	-	(Amon 2006)
Int-F-3	Intensive meadow with earlier harvesting dates; second cut	-	-	19.5	-	(Amon 2006)
Int-F-3	Intensive meadow with earlier harvesting dates; third cut	-	-	19.3	-	(Amon 2006)
Int-S-3	Intensive meadow with later harvesting dates; first cut	-	-	19.1	-	(Amon 2006)
Int-S-3	Intensive meadow with later harvesting dates; second cut	-	-	19.5	-	(Amon 2006)
Int-S-3	Intensive meadow with later harvesting dates; third cut	-	-	18.6	-	(Amon 2006)
Biomass description	**Remarks**	**Carbon (wt.%)**	**Ash (wt%)**	**Higher heating value (MJ kg-1)**	**Lower heating value (MJ kg-1)**	**Source**
MEAN		45.54	7.50	18.85	17.03	
MEDIAN		45.45	7.49	18.9	17.02	
SD		± 1.36	± 1.72	± 0.58	± 0.51	

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Table A4: Biorefinery Model

Conversion process	Combined heat and power via Stirling motor	Syngas methanation	Enzymatic fermentation of lignocellulosic biomass	Comments
Biofuel produced	Electricity	Methane	Ethanol	
Co-product	Thermal energy	None	Electricity	
Biorefinery capacity	130 kW h^{-1}	750 MW h^{-1}	450 tons EtOH per year	
Biomass input, hourly (kg DM ha^{-1})	28	160	-	
Biomass input, annually (t DM y^{-1})	150	1300	3640	
Biofuel conversion efficiency	0.23	0.55	0.487	based on LHV of biomass input
Electrical efficiency	0.23	-	0.045	
Thermal efficiency	0.67	-	-	
Total energy conversion efficiency	0.9	0.55	0.532	
External energy input	yes	yes	No	
References	(Primas 2007; Campbell, Lobell et al. 2009)	(Jungbluth, Chudacoff et al. 2007)	(Sheehan, Aden et al. 2003; Jungbluth, Chudacoff et al. 2007)	
Scaling factor biorefinery	10	0,1	1	A small gasification plant was assumed. As realized today, gasification of biomass would imply the biggest biorefinery.
Number of participating farms	5	30	75	Rounded up for secured biomass supply
Distance farm to biorefinery (km)	50	100	150	Used as mean for the transport of biomass to the biorefinery.
Distance biorefinery to well (km)	0	200	200	Used as mean for the transport of biofuel to well (gas station).

Table A5: DOC leaching

DOC leaching (measurement 2003) (Klumpp, Soussana et al. 2007)	mesocosm	[g C m^{-2} y^{-1}]		
constant low disturbance	LL	4.4	± 0.50	
shift to high disturbance	LH	5.8	± 0.60	
shift to low disturbance	HL	5.1	± 0.20	
constant high disturbance	HH	6.8	± 0.30	
	range	**4 to 6**		[g C m^{-2} y^{-1}]
Conclusions from authors (Klumpp, Soussana et al. 2007):				
Gradient 1: DOC loss increases with incline in slope.				
Gradient 2: DOC loss increases with disturbance (eg cutting frequency)				
Values used for model farms:	**One-cut**	**Two-cut**	**Three-cut**	unit
Mountain	50	55	60	kg C ha^{-1} y^{-1}
Hillside	45	50	55	kg C ha^{-1} y^{-1}
Valley	40	45	50	kg C ha^{-1} y^{-1}

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Table A6: CO_2-fluxes of reference grasslands

Site	Year	NEE [Mg C $ha^{-1}y^{-1}$]	Cuts per year	Harvest (Mg C $ha^{-1}y^{-1}$)	Publication
Oensingen int.	2002	-6,69	5	4,61	(Ammann, Flechard et al. 2007)
Oensingen int.	2003	-2,15	3	2,40	(Ammann, Flechard et al. 2007)
Oensingen int.	2004	-5,17	4	4,02	(Ammann, Flechard et al. 2007)
Oensingen ext.	2002	-3,52	3	3,81	(Ammann, Flechard et al. 2007)
Oensingen ext.	2003	-0,71	3	2,19	(Ammann, Flechard et al. 2007)
Oensingen ext.	2004	-3,39	3	3,35	(Ammann, Flechard et al. 2007)
Neustift	2001	-0,22	3	3,17	(Gilmanov, Soussana et al. 2007)
M. Bondone	2004	-2,74	1	n.d.	(Gilmanov, Soussana et al. 2007)
Malga Arpaco	2003	-16,26	grazed	grazed	(Gilmanov, Soussana et al. 2007)

Table A7: CH_4 uptake in grasslands

Publication (Boeckx and Van Cleemput 2001)				
CH4 –uptake in European grassland (kg CH_4 ha^{-1} y^{-1})	2.5			
Values used for model farms:	One-cut	Two-cut	Three-cut	unit
Mountain	3	2,5	2	kg CH_4 ha^{-1} y^{-1}
Hillside	3	2,5	2	kg CH_4 ha^{-1} y^{-1}
Valley	3	2,5	2	kg CH_4 ha^{-1} y^{-1}

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